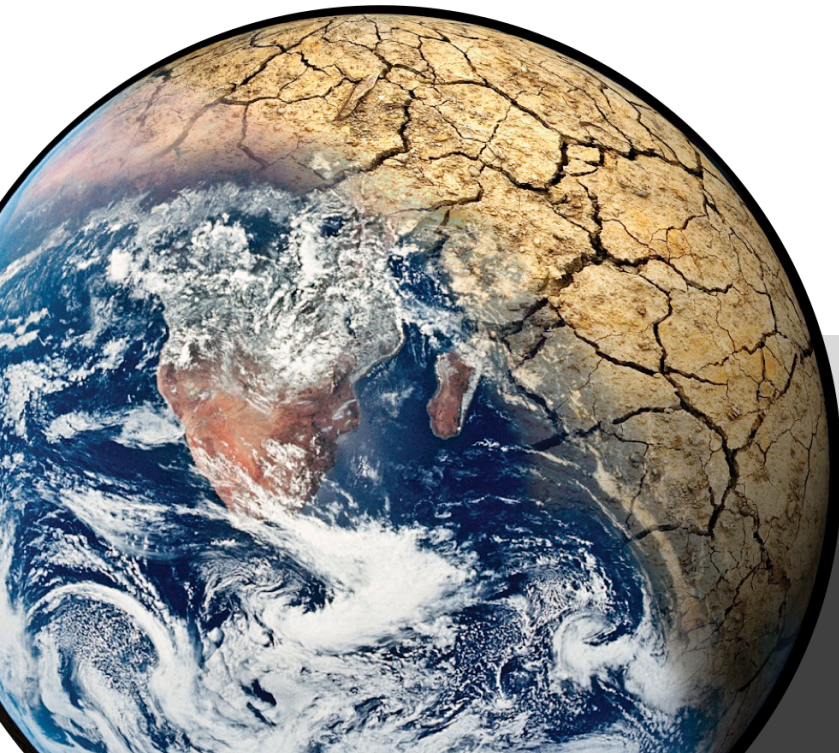


# An introduction to climate and Earth system modelling

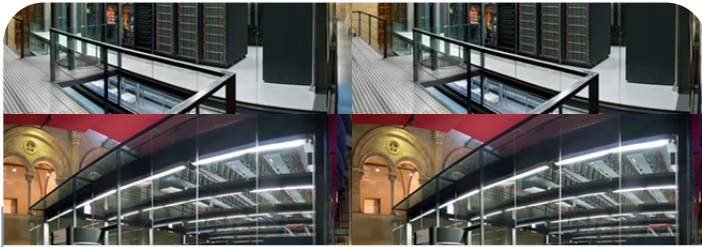


Pablo Ortega

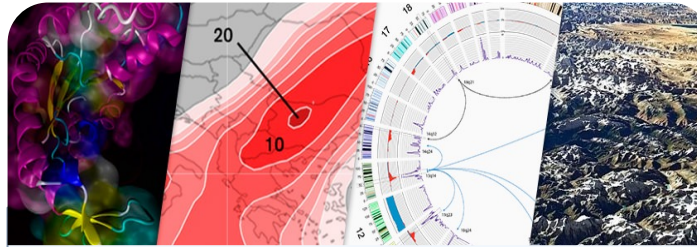
Earth Sciences Department [Climate Variability & Change]  
Barcelona Supercomputing Center

# Barcelona Supercomputing Center Centro Nacional de Supercomputación

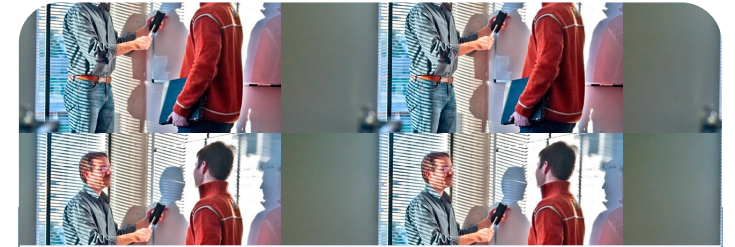
## BSC-CNS objectives



Supercomputing services  
to Spanish and EU researchers



R&D in Computer, Life, Earth  
and Engineering Sciences



PhD programme, technology  
transfer, public engagement

BSC-CNS is  
a consortium  
that includes

Spanish Government

60%



Catalan Government

30%



Univ. Politècnica de Catalunya

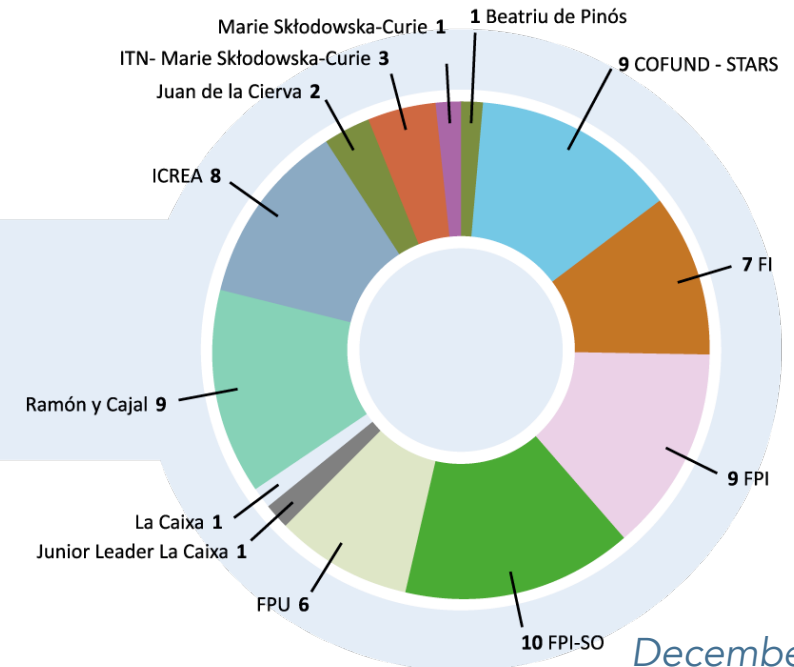
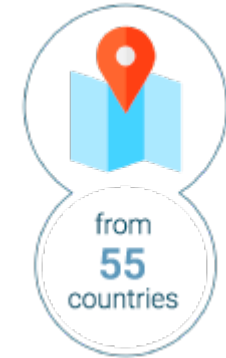
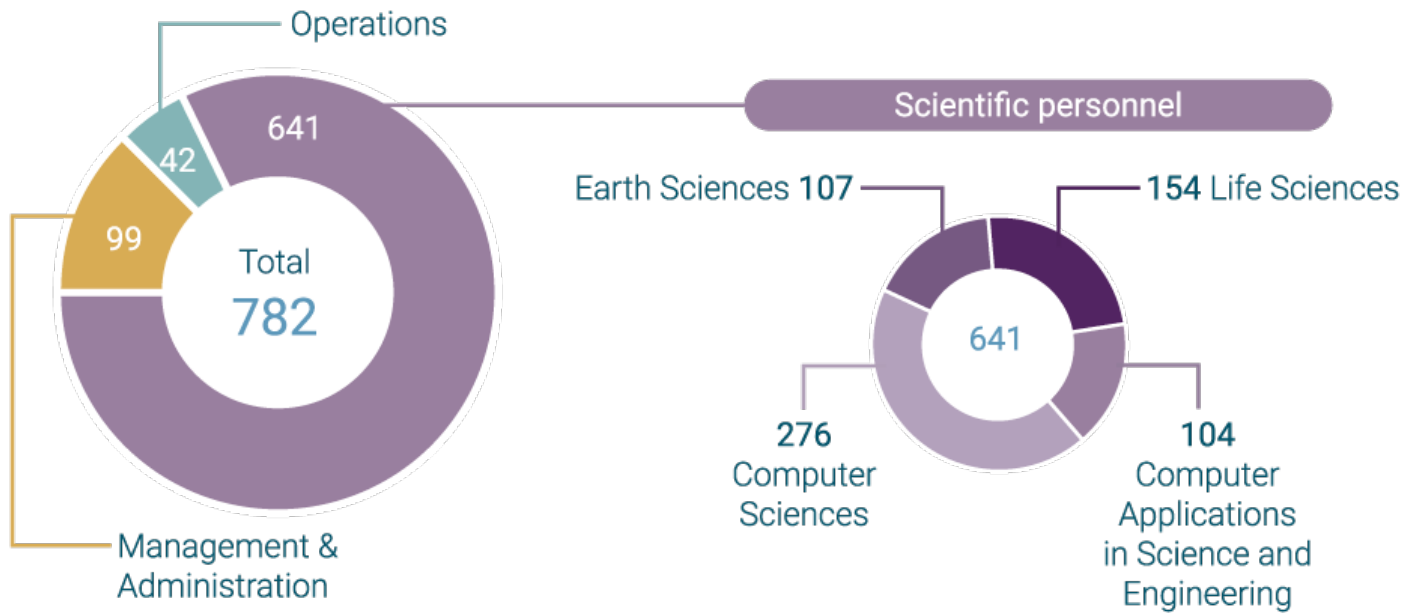
10%



# BSC Personnel



HR EXCELLENCE IN RESEARCH




# Mission of BSC Scientific Departments

A circular graphic with a background of colorful, abstract patterns resembling a digital or circuit board design.

## Computer Sciences

To **influence the way machines are built, programmed and used**: programming models, performance tools, Big Data, Artificial Intelligence, computer architecture, energy efficiency

A circular graphic with a background of a colorful, abstract pattern resembling a globe or a map of the Earth.

## Earth Science

To develop and implement global and regional state-of-the-art models for **short-term air quality forecasting** and **long-term climate applications**

A circular graphic with a background of colorful, abstract patterns resembling a molecular structure or a biological process.

## Life Sciences

To **understand living organisms** by means of theoretical and computational methods (molecular modeling, genomics, proteomics)

A circular graphic with a background of colorful, abstract patterns resembling a landscape or a map of the Earth.

## CASE

To **develop scientific and engineering software** to efficiently exploit super-computing capabilities on biomedics, geophysics, atmospheric, energy, social and economic





# Earth Sciences

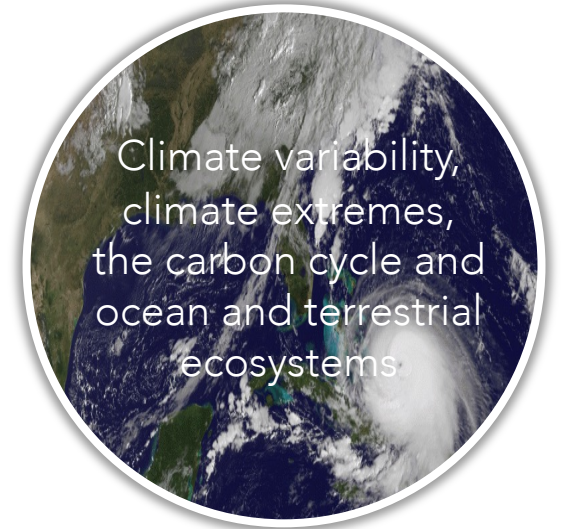
Environmental modelling and forecasting, with a particular focus on weather, climate and air quality

Atmospheric composition



Fundamental Understanding  
Forecasting Capabilities

Climate System



Services in broad range of users sectors



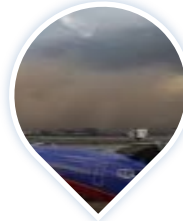
Infrastructures



Solar Energy



Urban development



Transport



Wind Energy



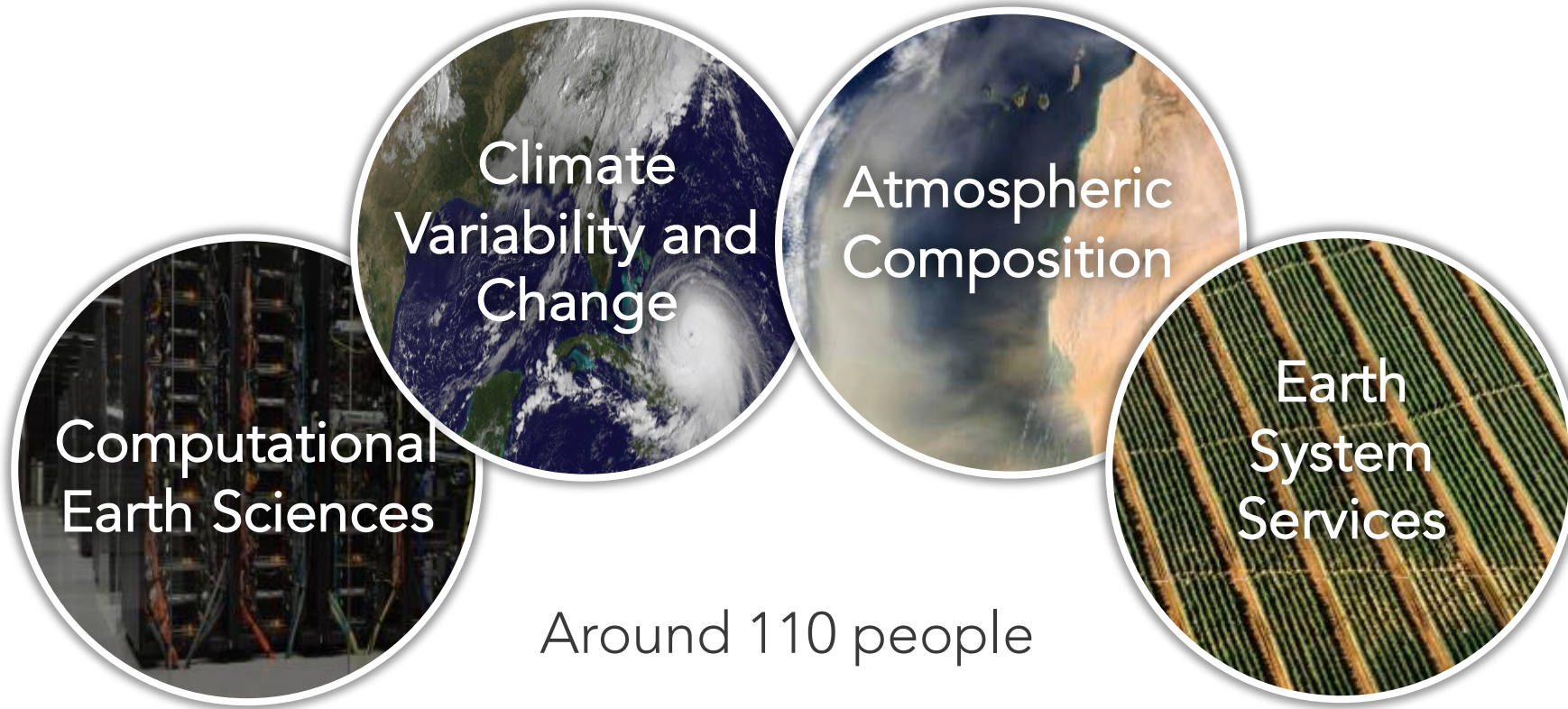
Agriculture



Insurance

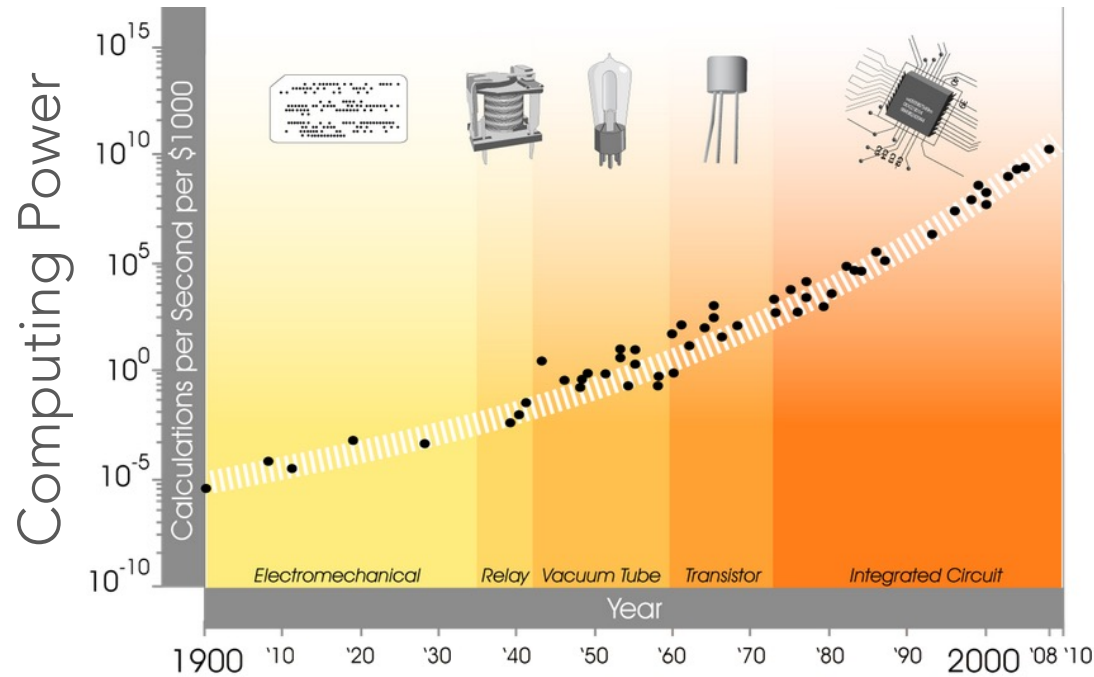
# Earth Science Department

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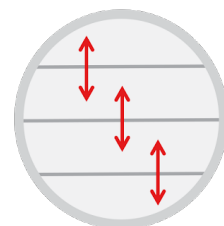


Head of the Department: **Francisco Doblas-Reyes**

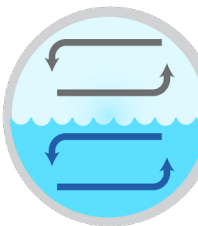
# Earth System (and HPC) evolution



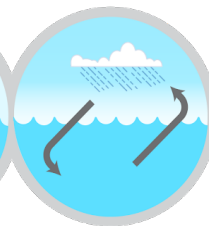
4th National Climate Assessment (US), Volume I



1890s  
Radiative  
Transfer



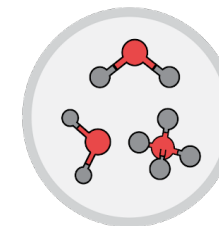
1960s  
Non-Linear  
Fluid Dynamics



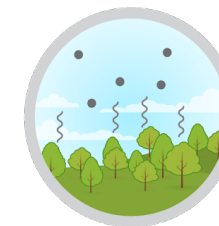
Hydrological  
Cycle



1970s  
Sea Ice and  
Land Surface



1990s  
Atmospheric  
Chemistry



2000s  
Aerosols and  
Vegetation



2010s  
Biogeochemical  
Cycles and Carbon

Energy Balance Models

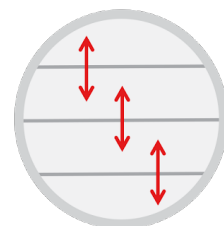
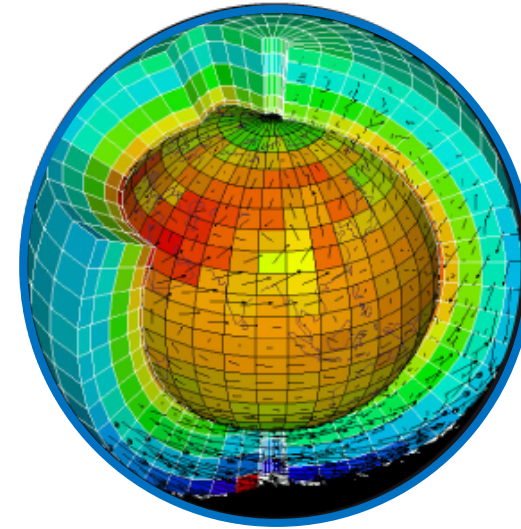
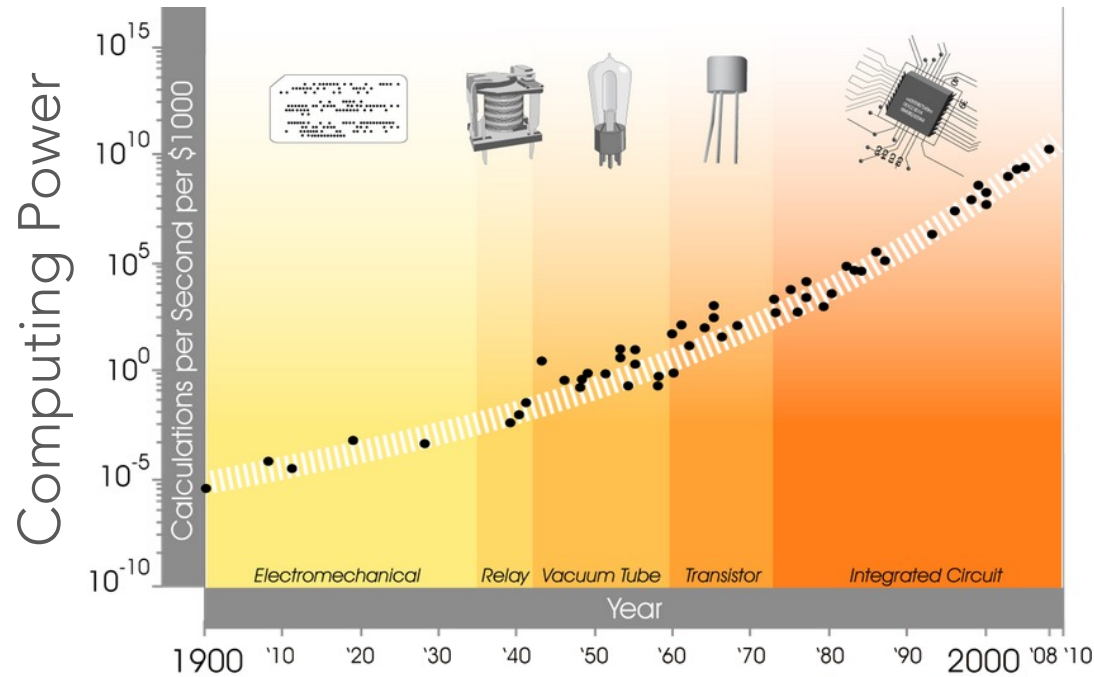
Atmosphere-Ocean General Circulation Models

Earth System Models

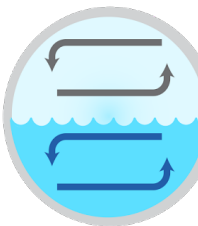
Earth System Models



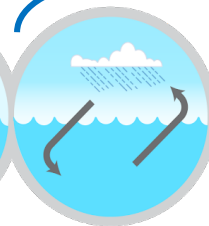
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1890s  
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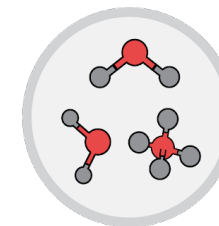
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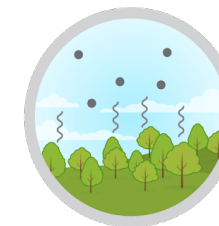
Hydrological  
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1970s  
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Energy Balance Models

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Earth System Models

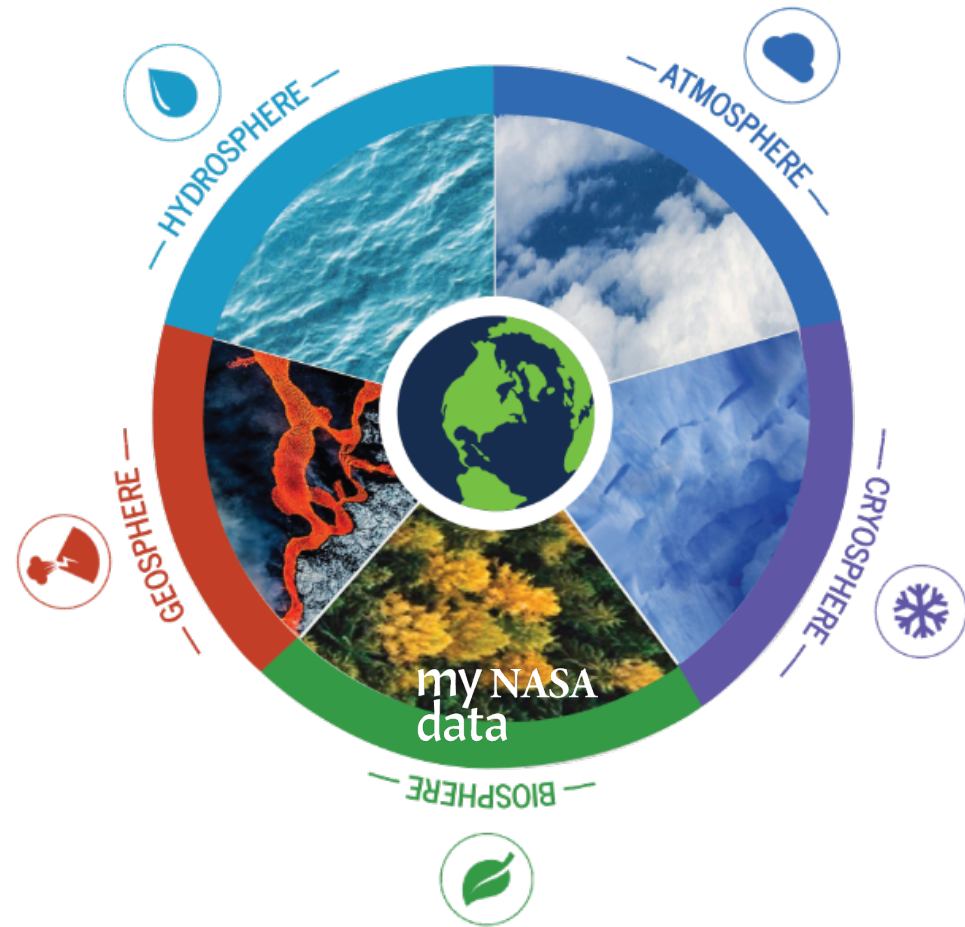
Earth System Models



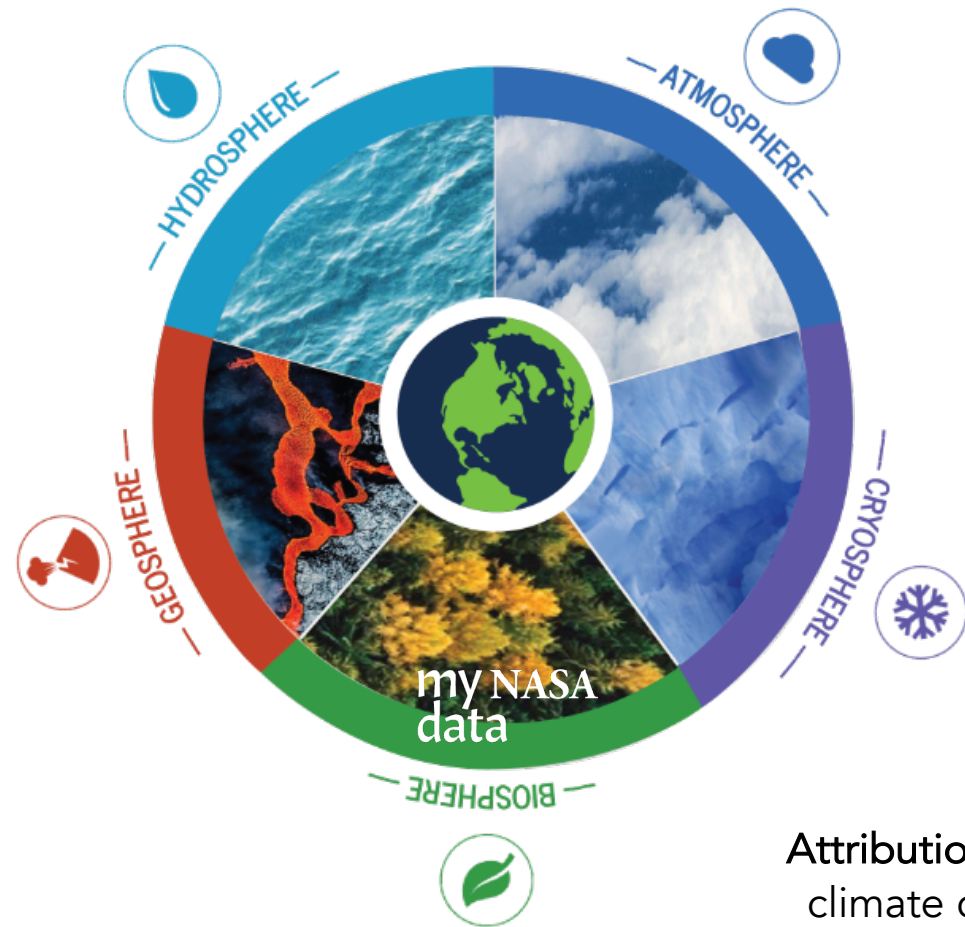
# Earth System Models (as *experimentation labs*)

*In essence*

Mathematical representation of the Earth system through the fundamental laws governing the evolution within and interactions between the different Earth system components.



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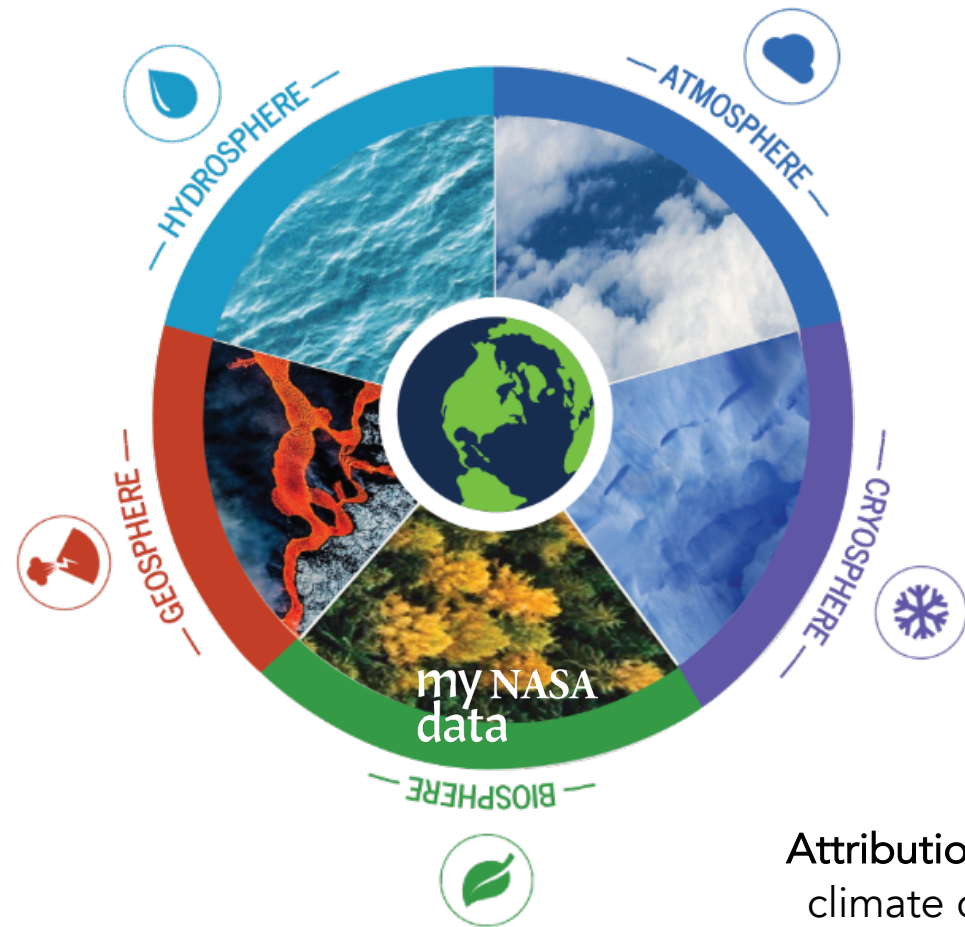
*In Practice*

ESMs are our major tool to generate scientific understanding via hypothesis testing on topics as diverse as:

Attribution of past climate changes



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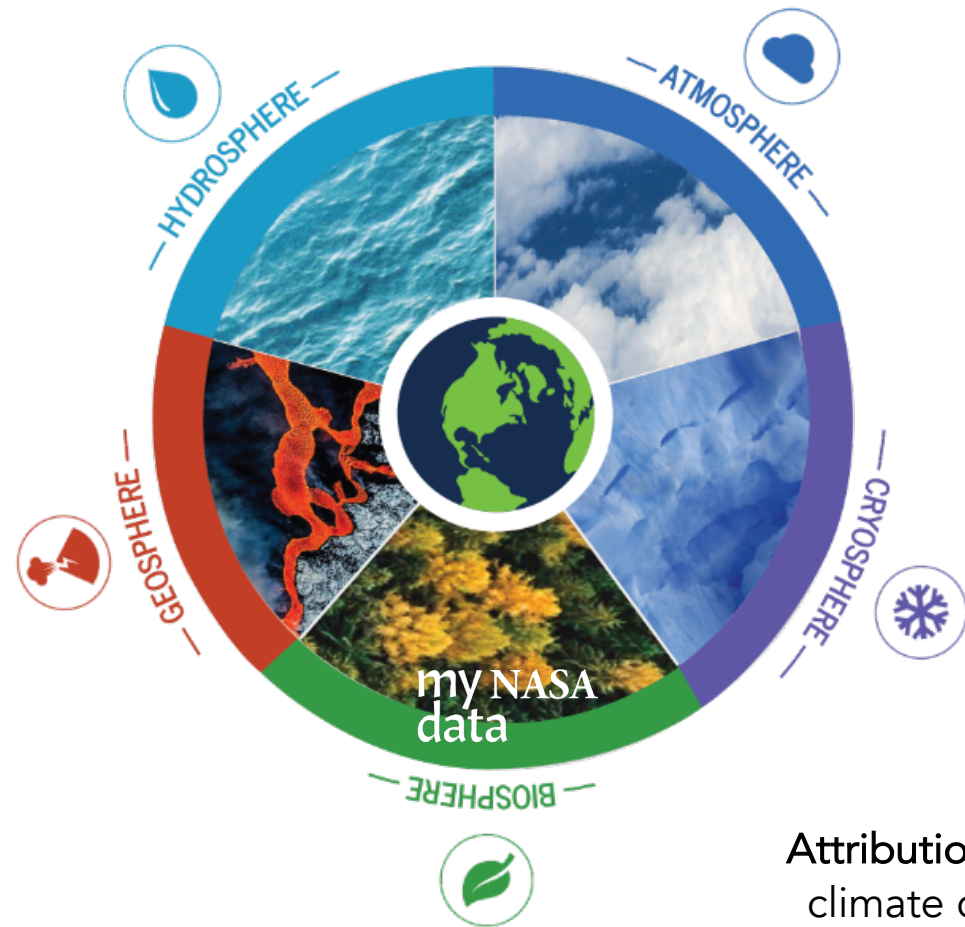
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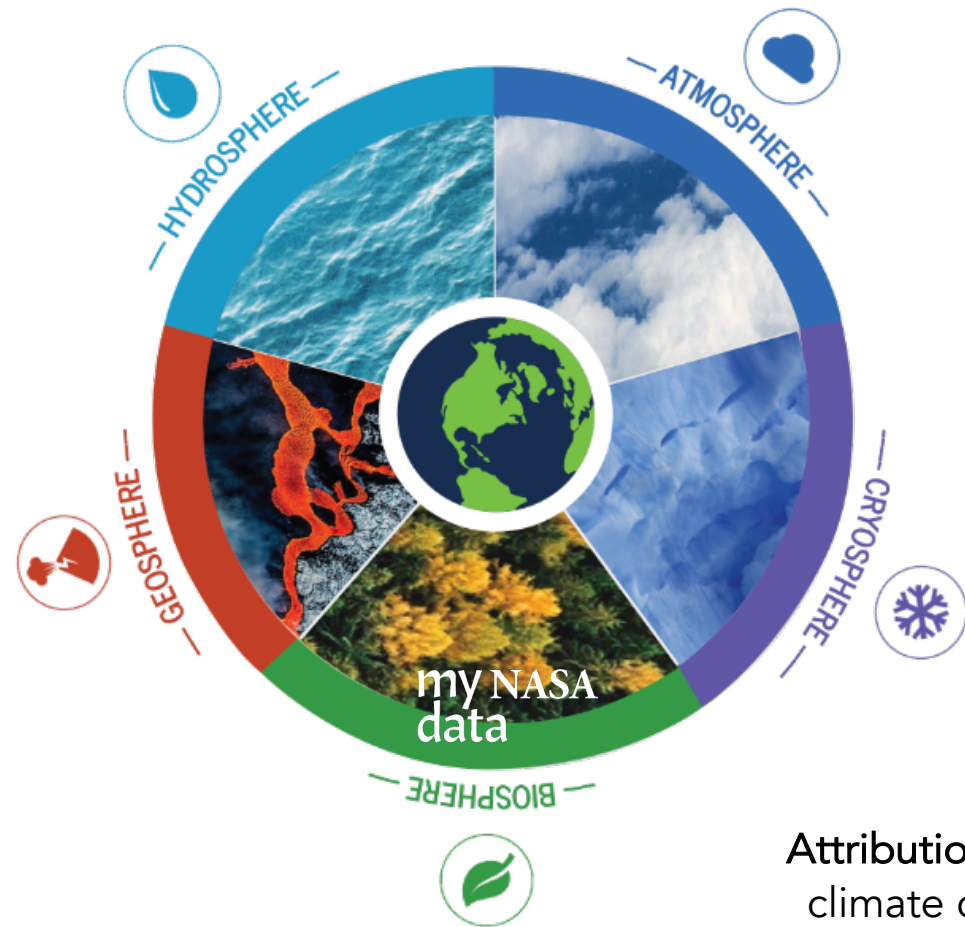
Adaptation/Mitigation of future climate change

Risk of tipping (Irreversible Changes)





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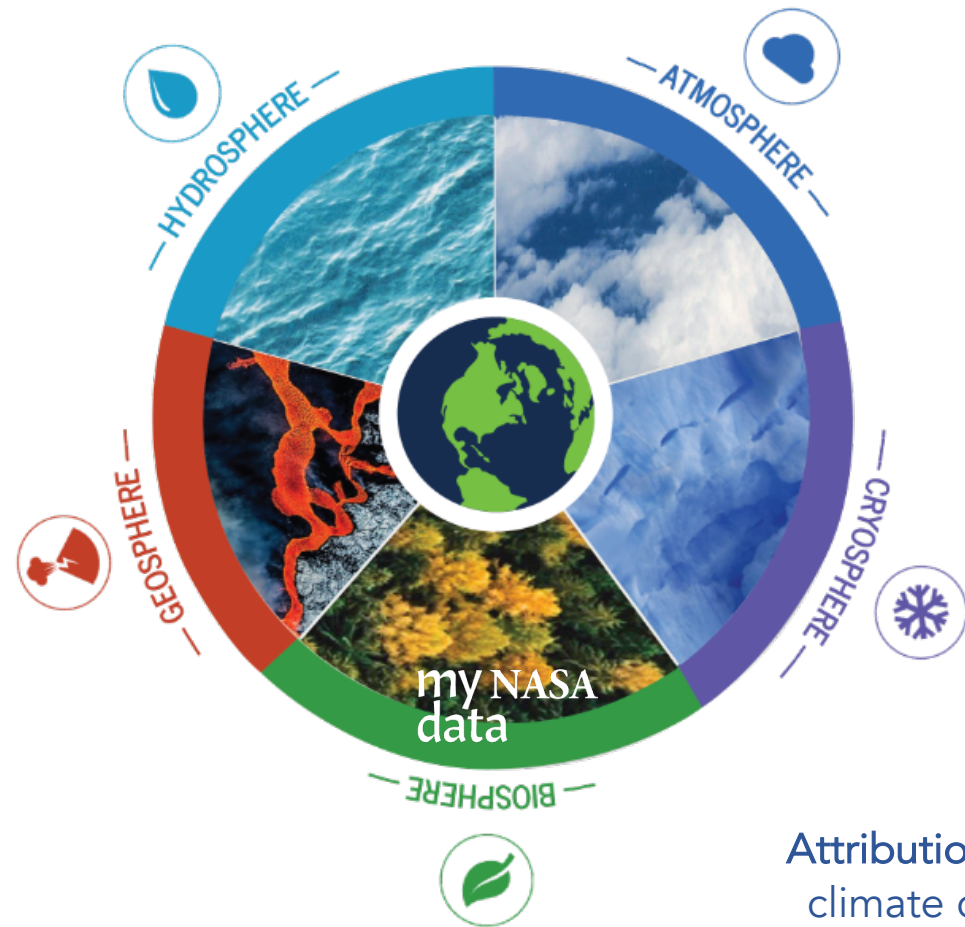
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Near-term climate prediction

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Risk of tipping (Irreversible Changes)

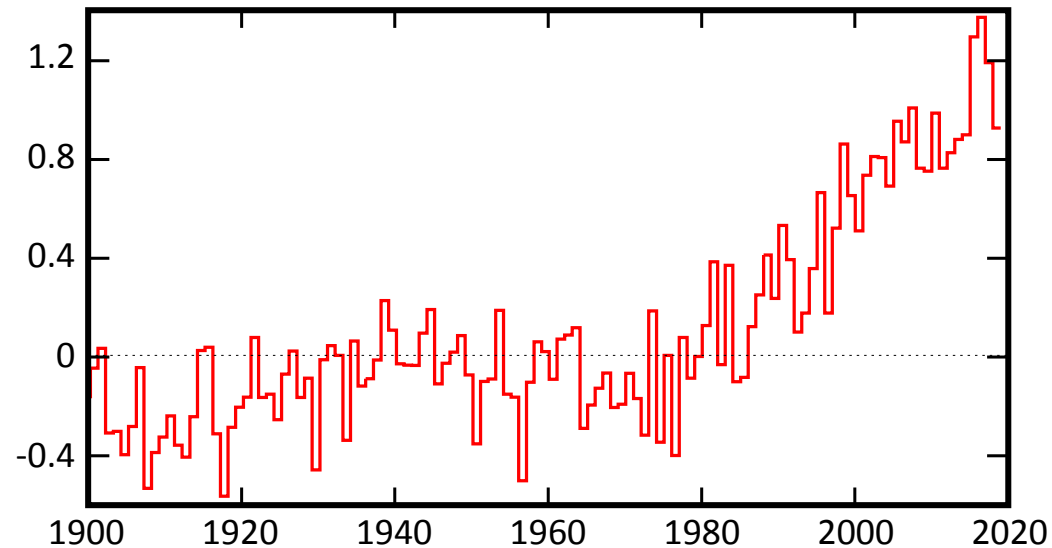


Near-term climate prediction

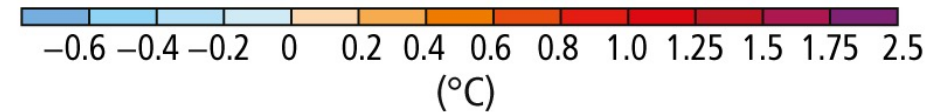
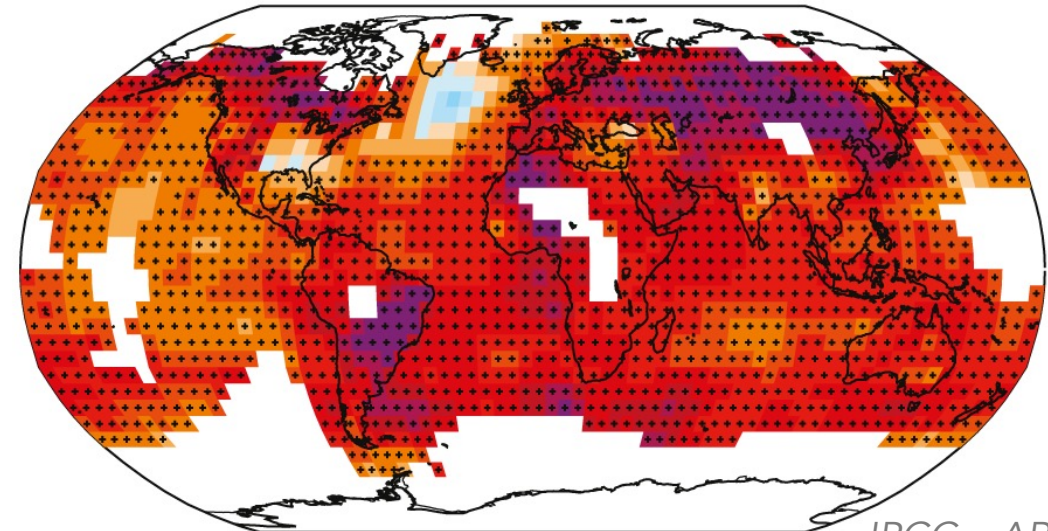
# Earth System Models for **climate change attribution**

ESMs can help understand the main drivers of past changes in climate

Observed Global Surface Temperature anomaly (in K)



Observed Change in surface temperature (1901-2012)



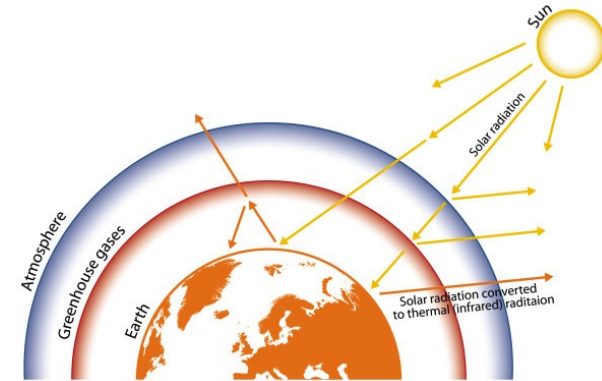
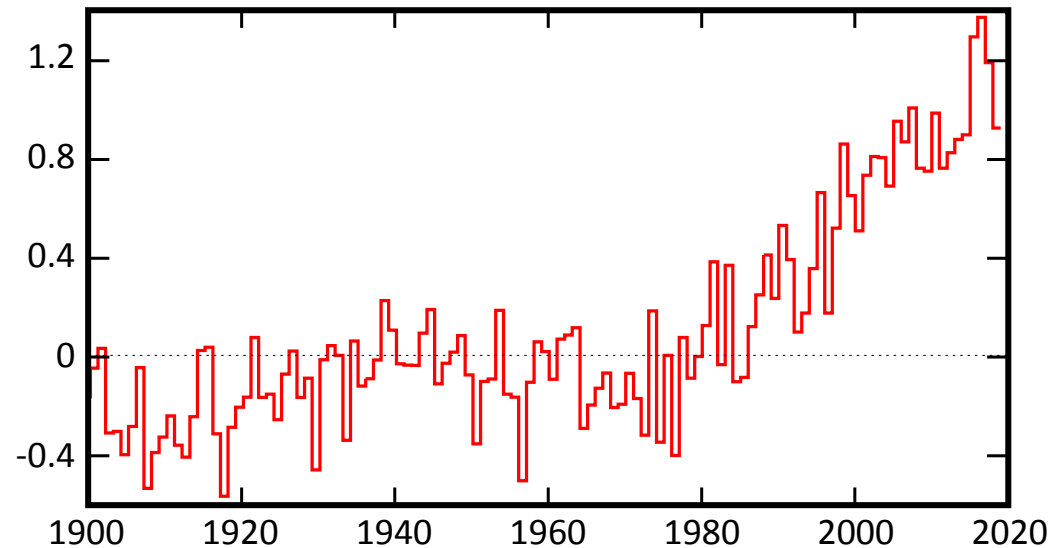
IPCC – AR5 – Chapter 2

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External radiative forcers

Observed Global Surface Temperature anomaly (in K)



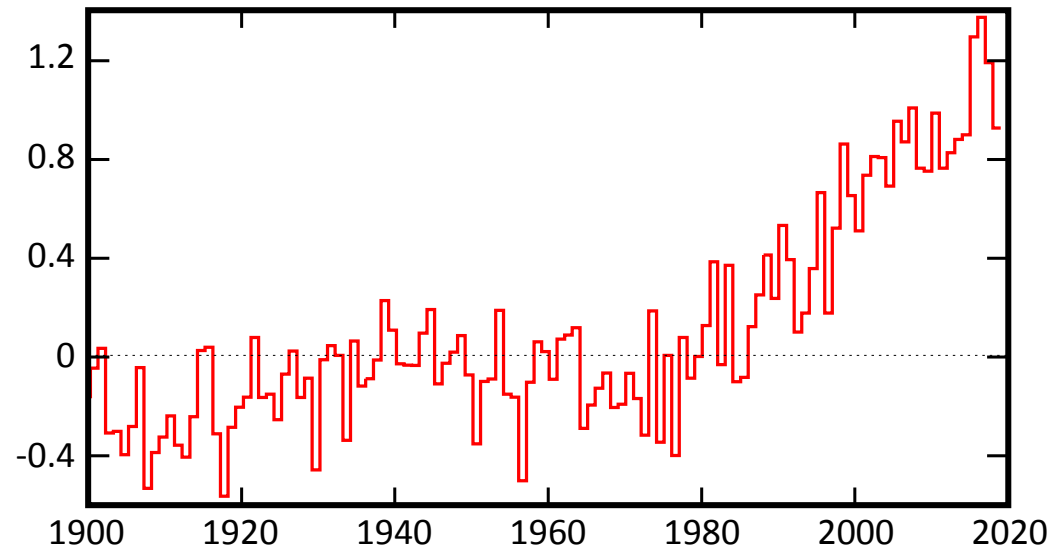
[www.climatica.org.uk](http://www.climatica.org.uk)



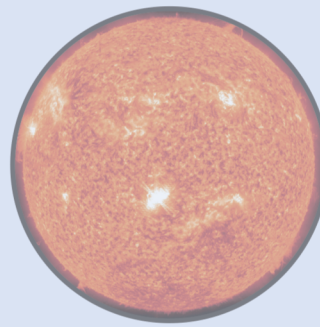
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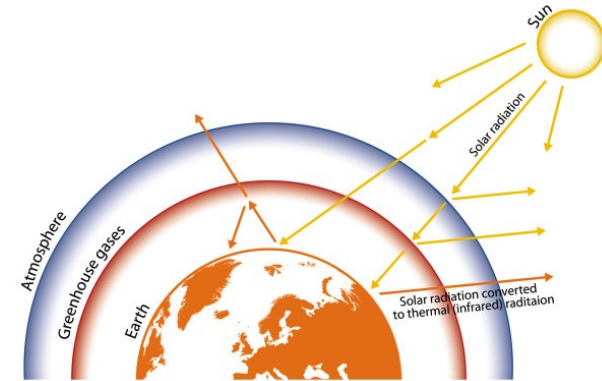


Solar Irradiance



Volcanic Aerosols

**Natural Origin**

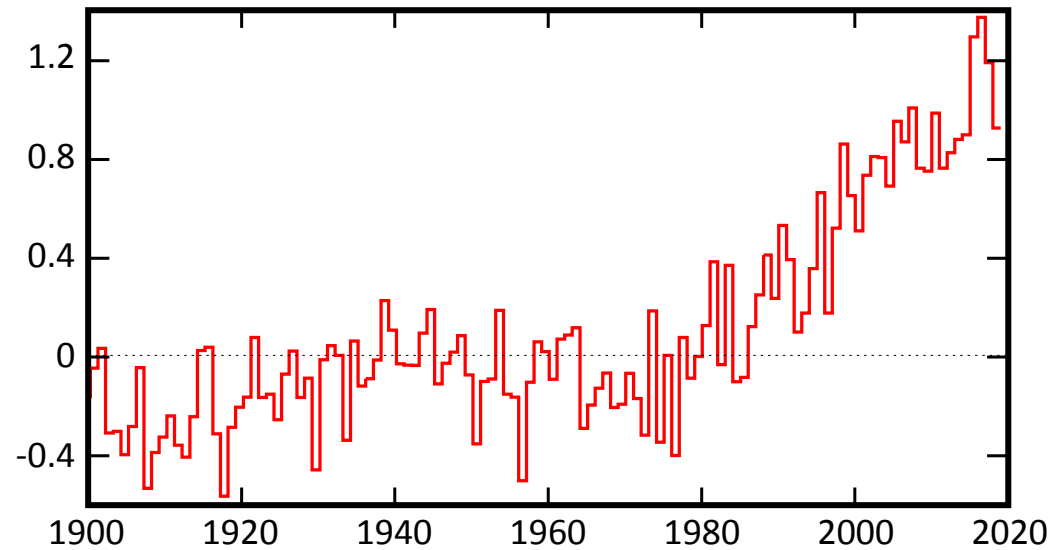


[www.climatica.org.uk](http://www.climatica.org.uk)

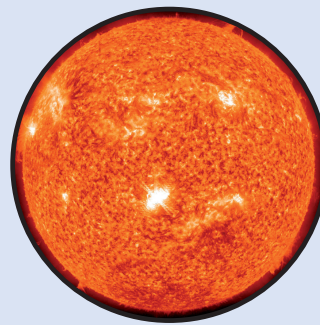
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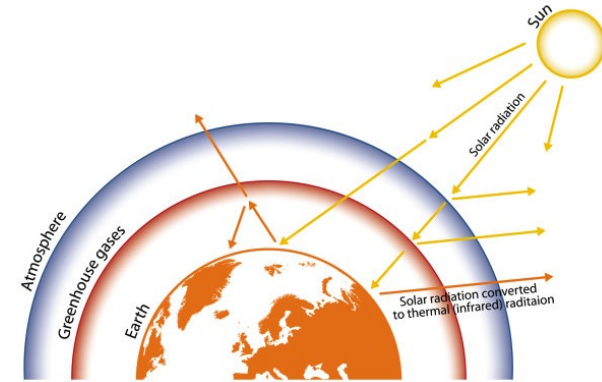


Solar Irradiance

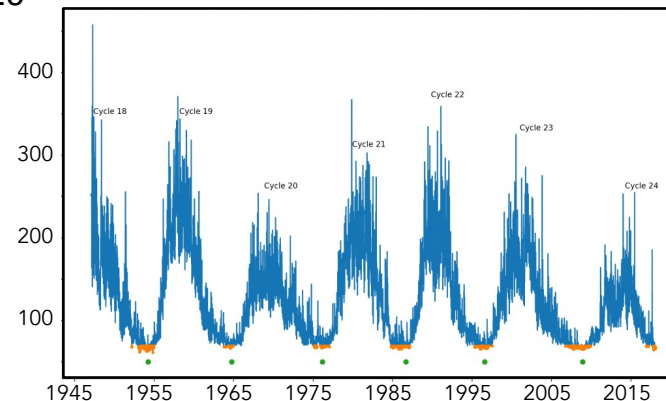


Volcanic Aerosols

Natural Origin



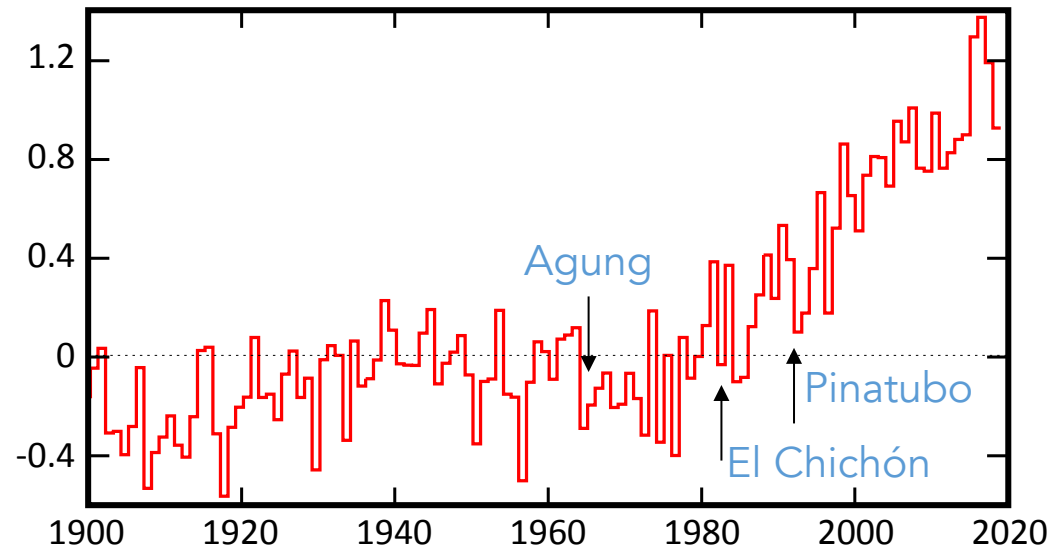
[www.climatica.org.uk](http://www.climatica.org.uk)



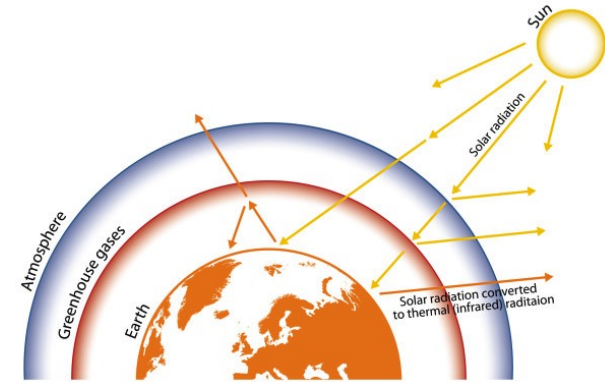
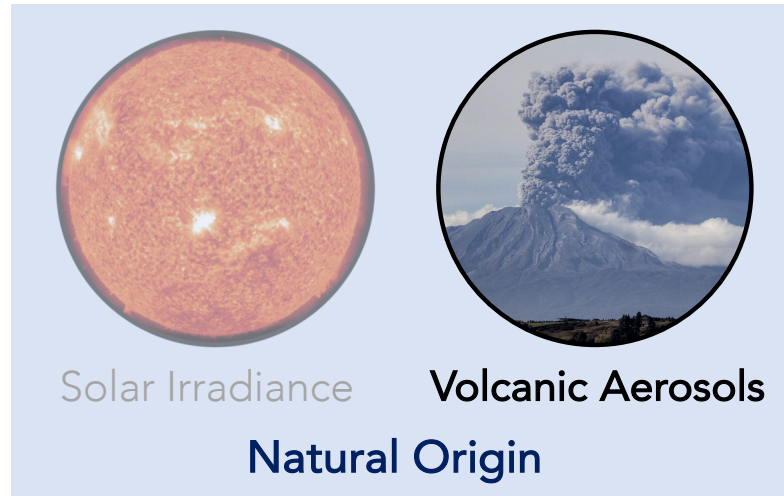
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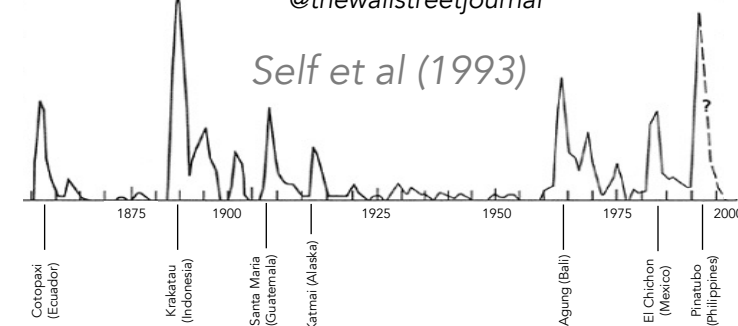
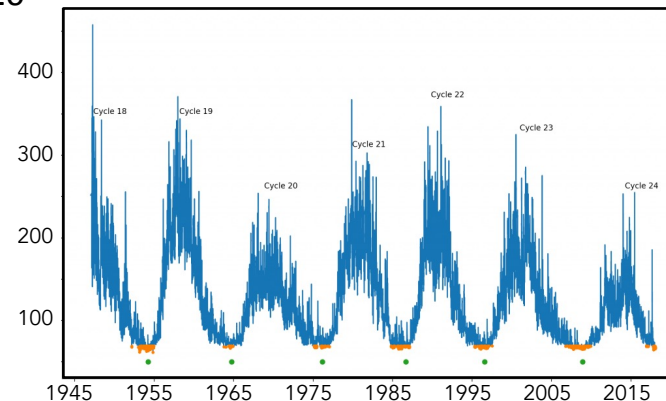


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@thewallstreetjournal

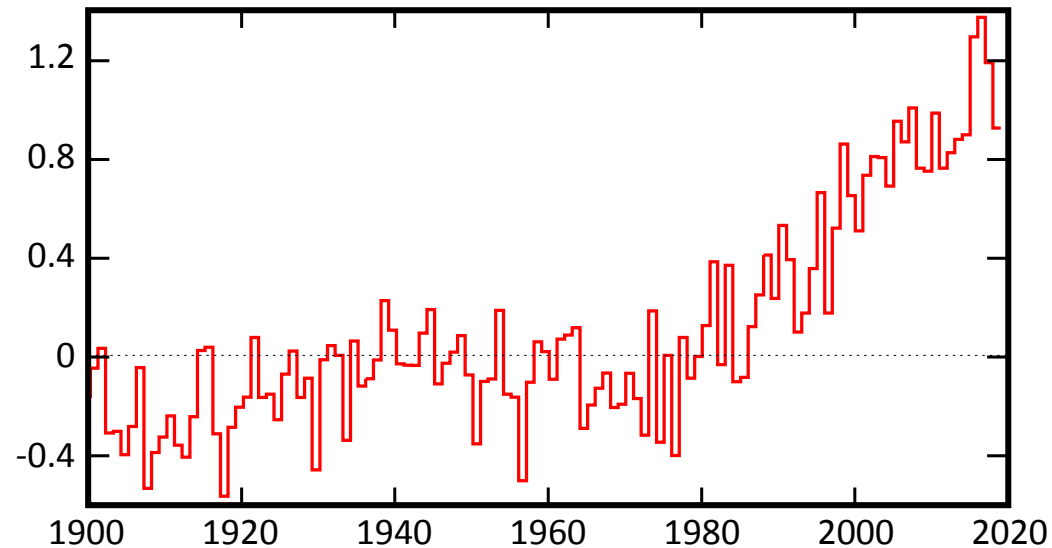
Self et al (1993)



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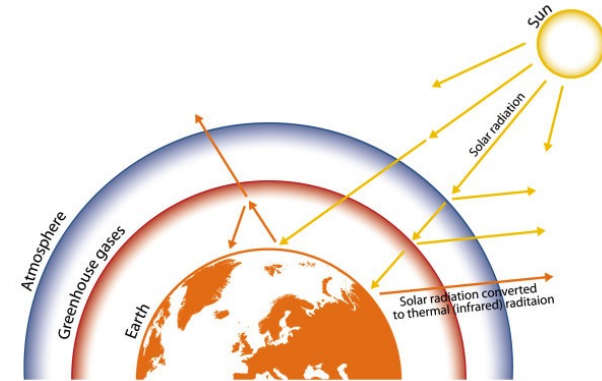


Greenhouse Gasses  
Sulfate Aerosols



Land Cover

**Human Origin**



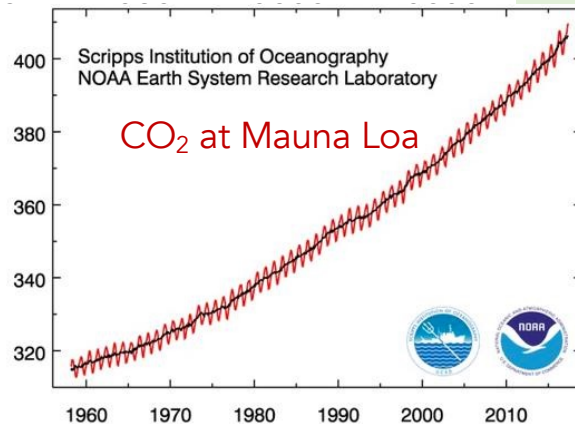
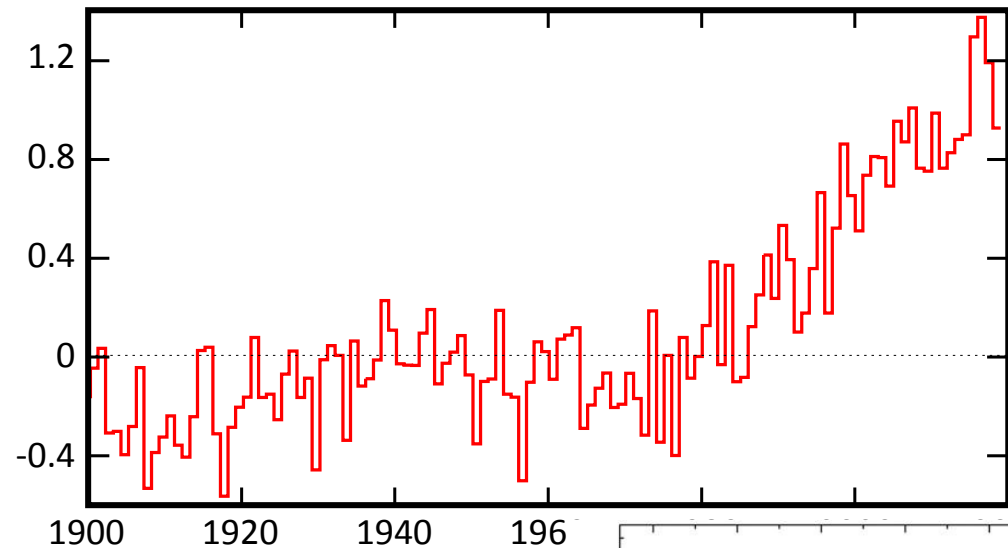
[www.climatica.org.uk](http://www.climatica.org.uk)



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## External radiative forcers



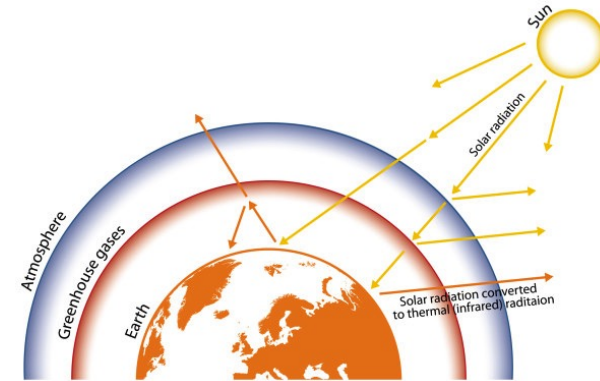
**Greenhouse Gasses**

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Land Cover

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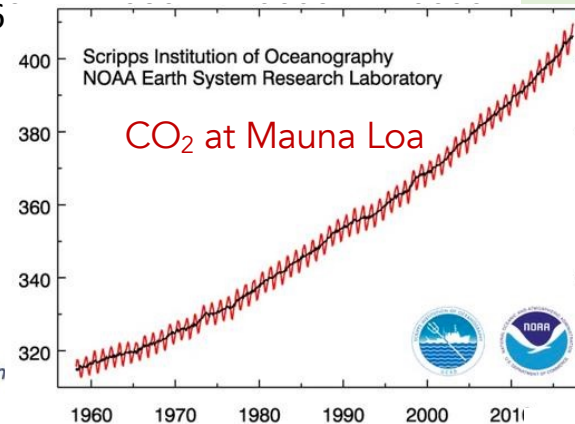
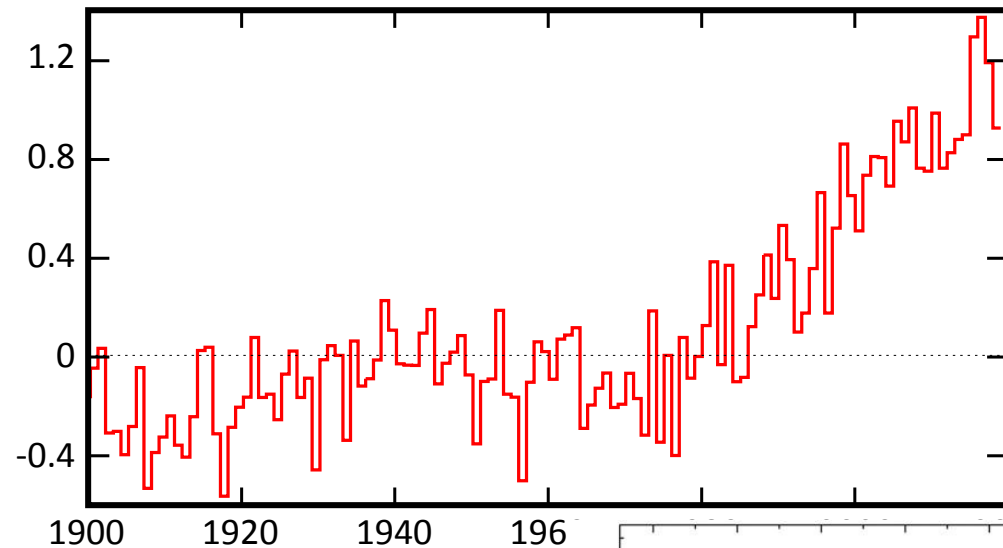


[www.climatica.org.uk](http://www.climatica.org.uk)

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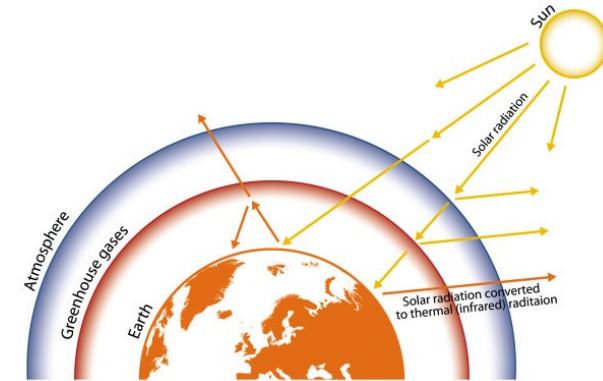
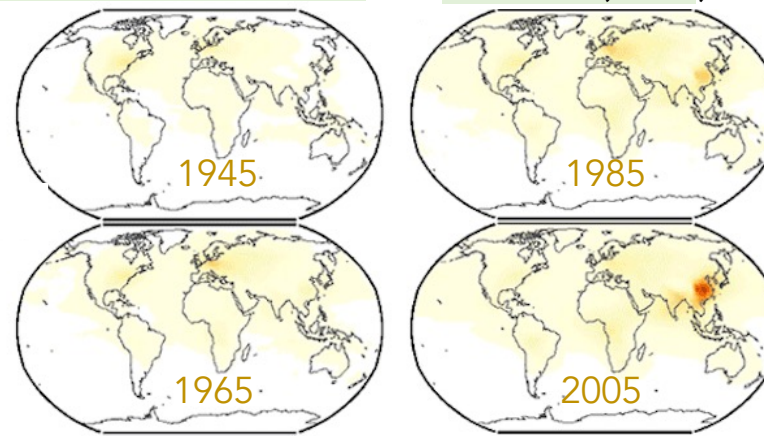
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Sulfate Aerosols



Land Cover

Human Origin

Kinne (2019)

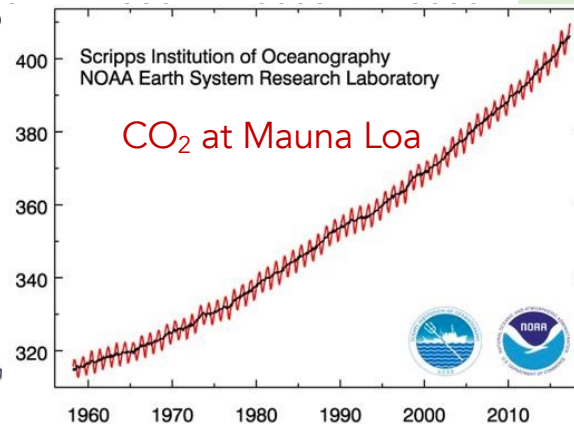
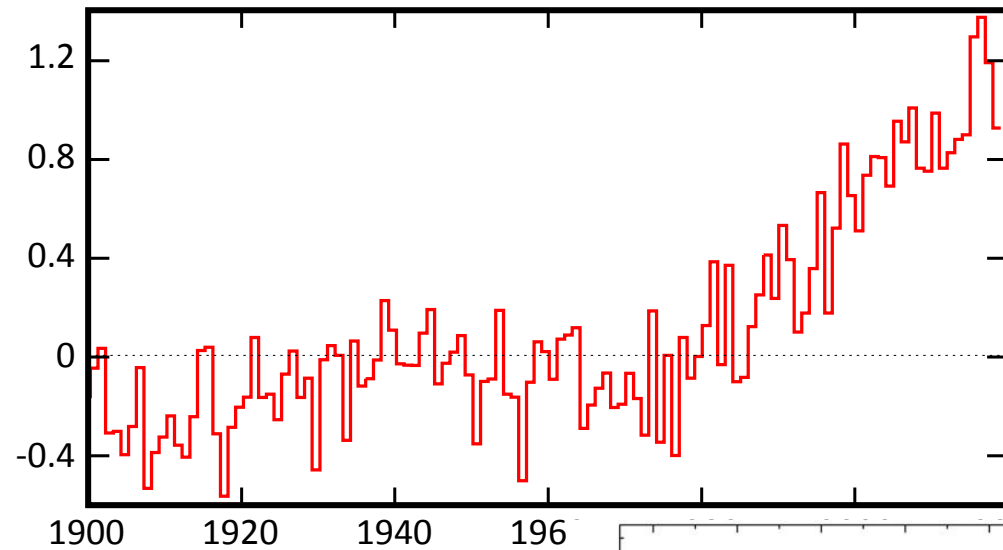


[www.climatica.org.uk](http://www.climatica.org.uk)

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## External radiative forcers



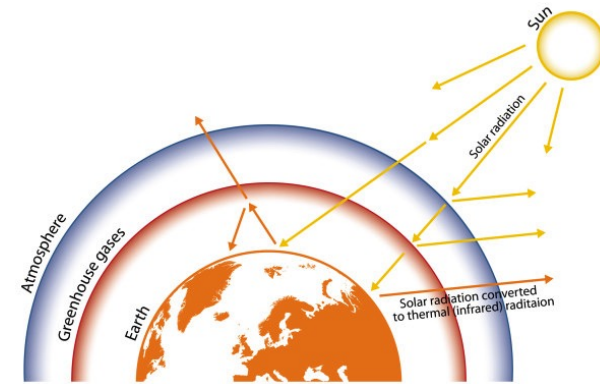
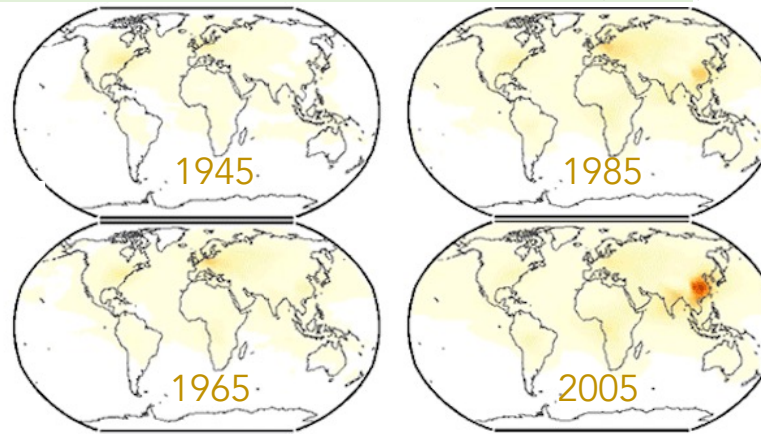
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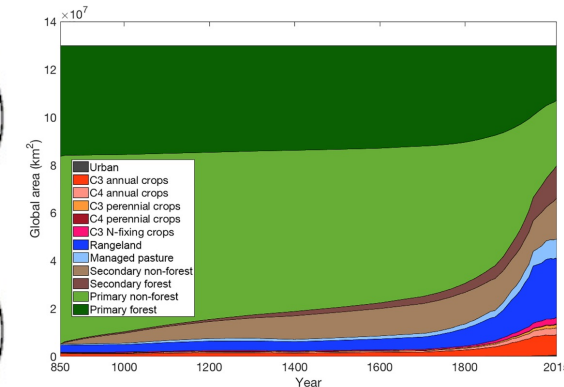
Human Origin

Kinne (2019)



[www.climatica.org.uk](http://www.climatica.org.uk)

## Land use in last millennium



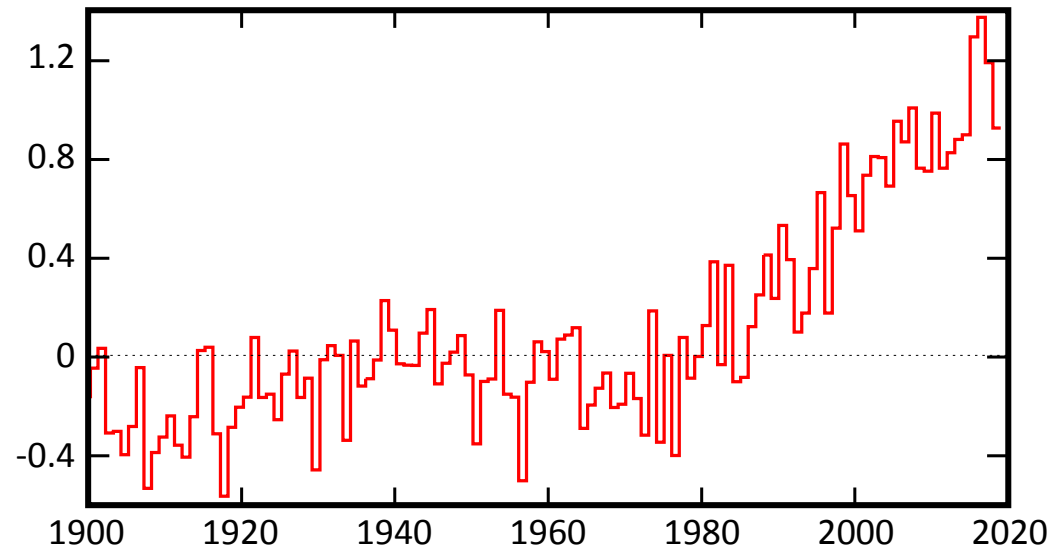
Jungclauss et al (2017)



# Earth System Models for **climate change attribution**

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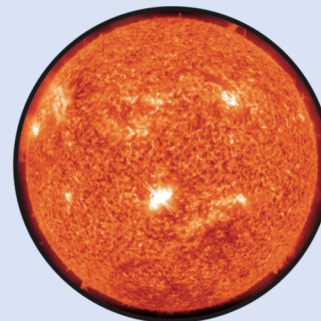
Observed Global Surface Temperature anomaly (in K)



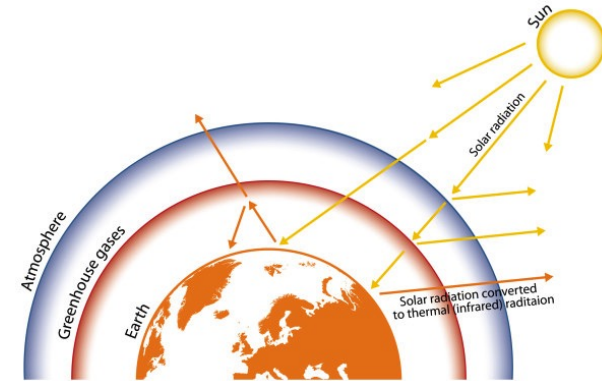
## External radiative forcers



Human Origin



Natural Origin



[www.climatica.org.uk](http://www.climatica.org.uk)

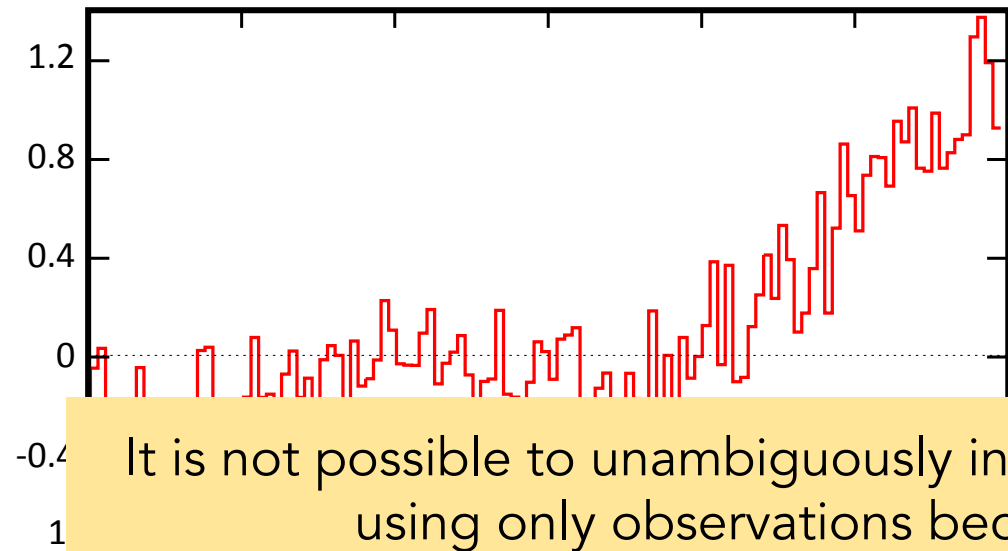
Which are the most important factors?



# Earth System Models for **climate change attribution**

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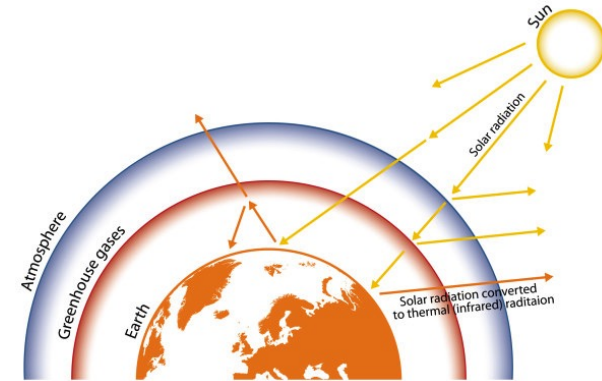
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External radiative forcers

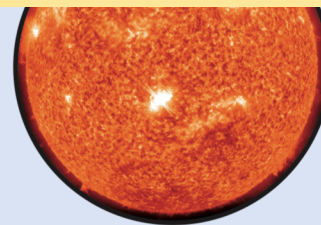


Human Origin



www.climatica.org.uk

It is not possible to unambiguously infer the role of the different drivers on the observed changes using only observations because all **influences have occurred concomitantly**

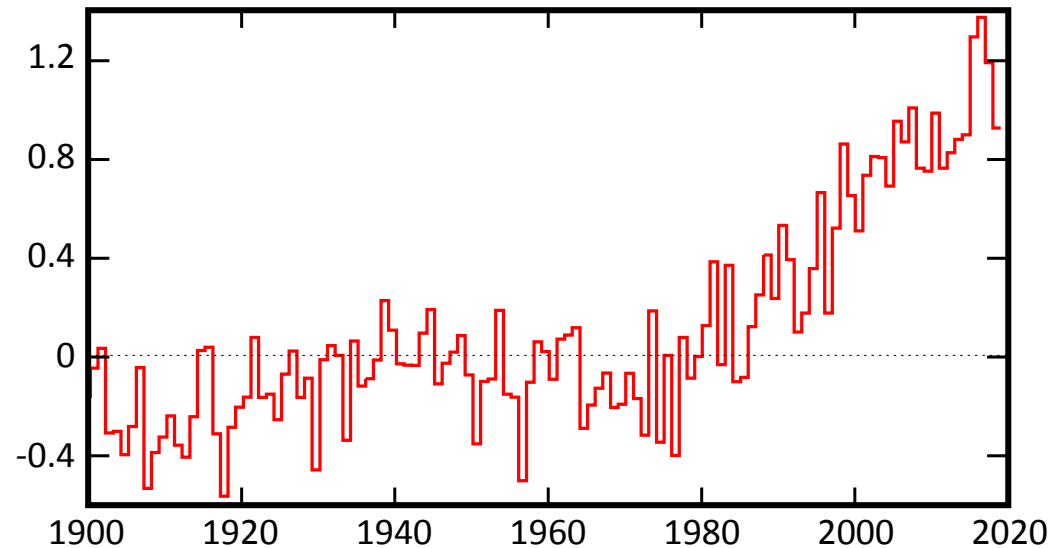


Natural Origin

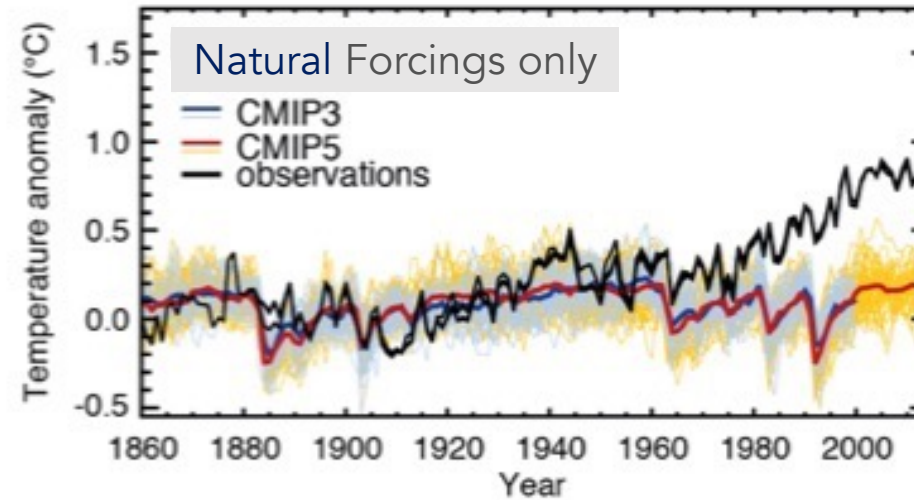
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Observed Global Surface Temperature anomaly (in K)



IPCC – AR5 – Chapter 10

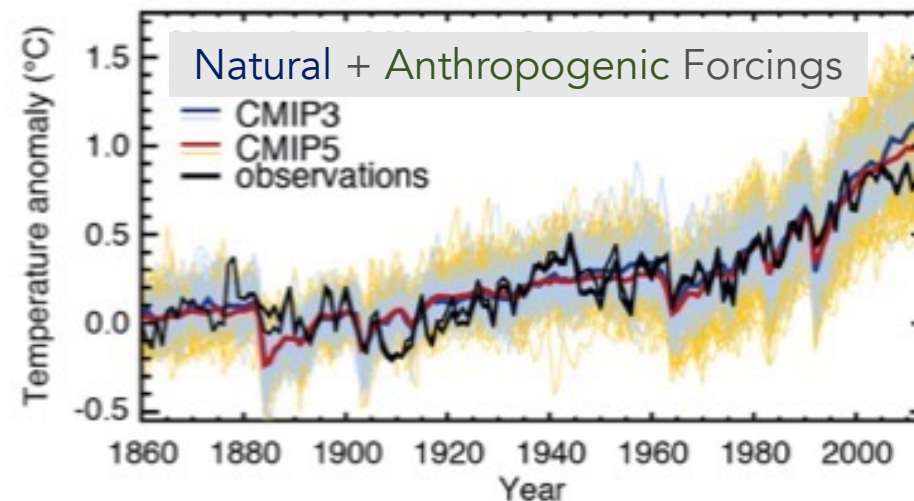
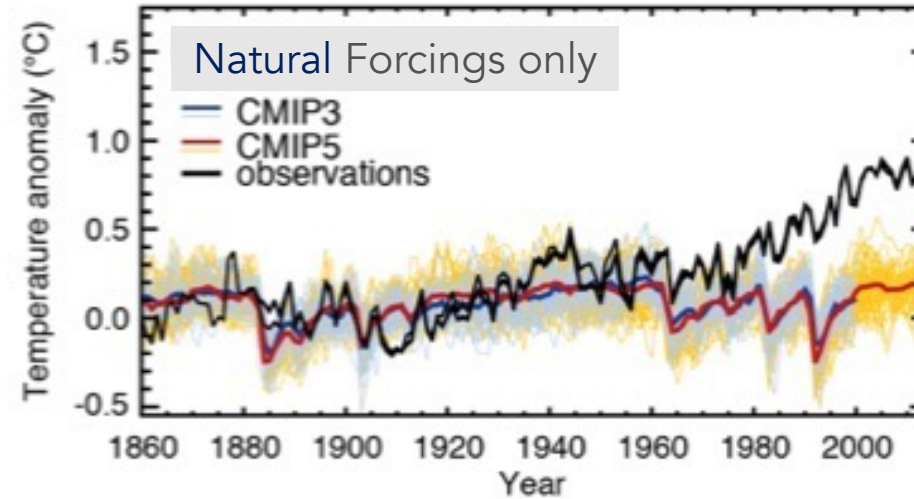
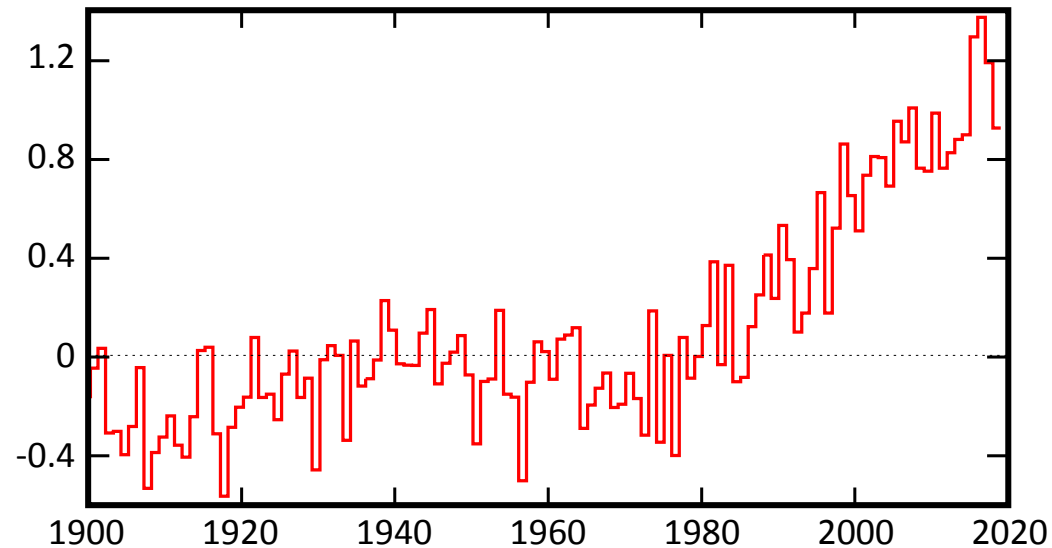


# Earth System Models for **climate change attribution**

ESMs can help understand the main drivers of past changes in climate

*IPCC – AR5 – Chapter 10*

Observed Global Surface Temperature anomaly (in K)

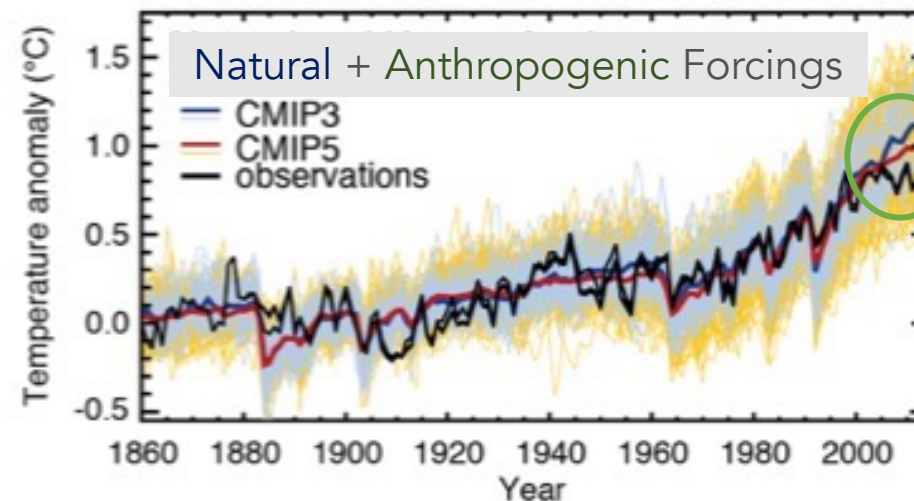
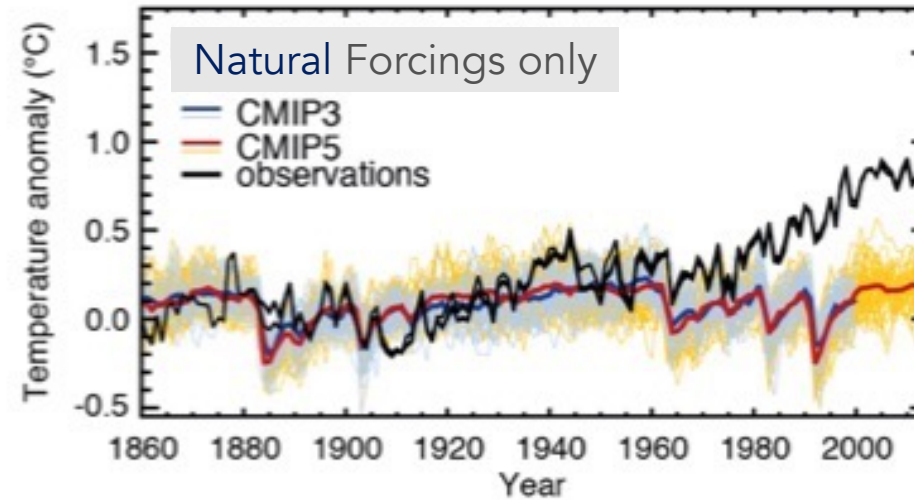
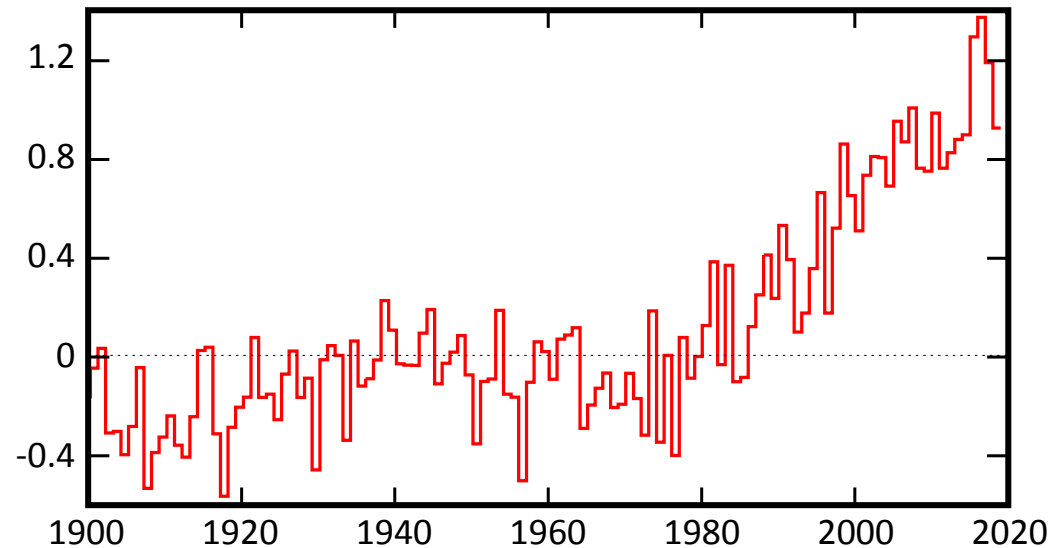


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ESMs can help understand the main drivers of past changes in climate

IPCC – AR5 – Chapter 10

Observed Global Surface Temperature anomaly (in K)



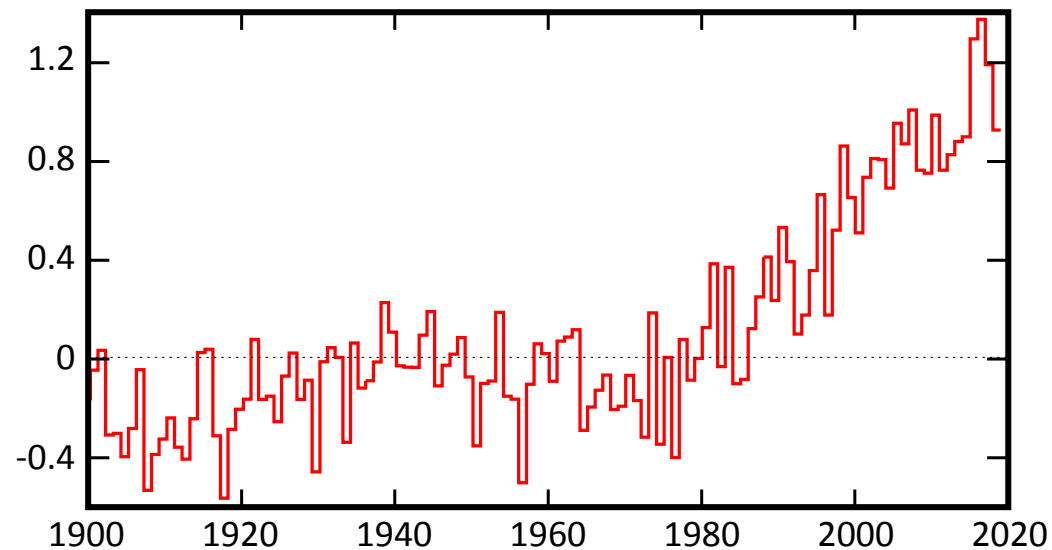
What other factors can explain the discrepancies?



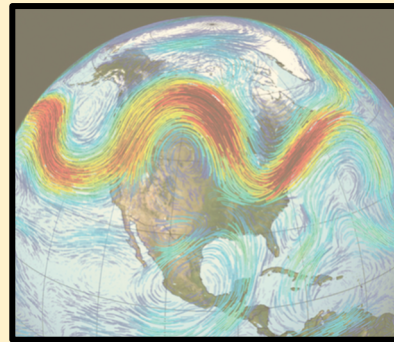
# Earth System Models for **climate change attribution**

ESMs can help understand the main drivers of past changes in climate

Global mean Surface Temperature anomaly (in K)



## Internal Climate Variability



Atmosphere



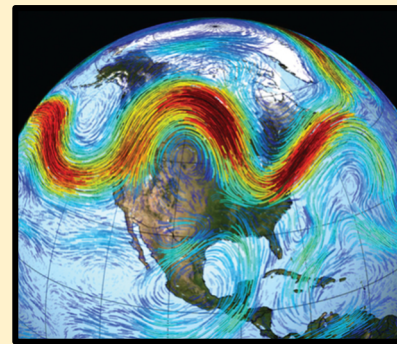
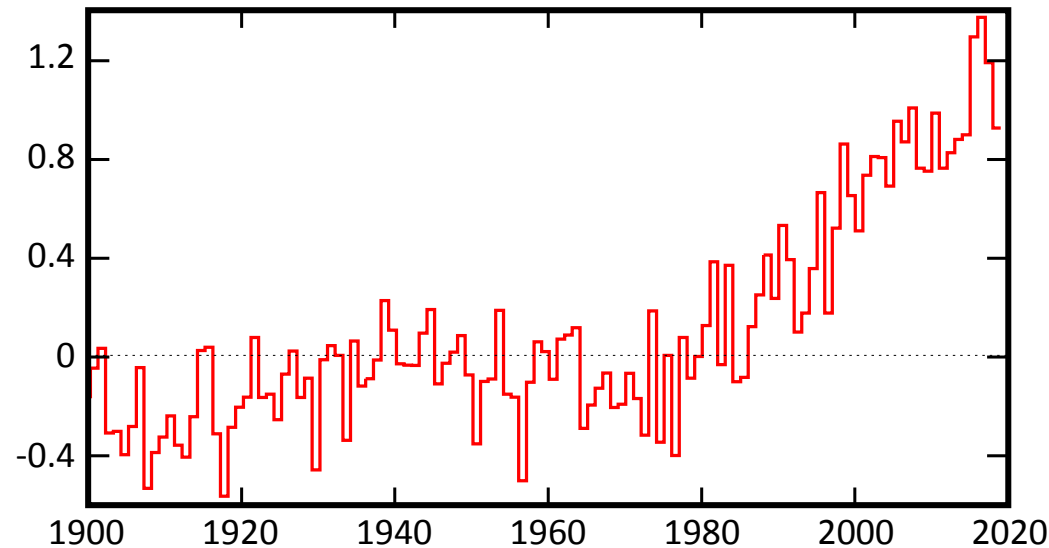
Ocean

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ESMs can help understand the main drivers of past changes in climate

## Internal Climate Variability

Global mean Surface Temperature anomaly (in K)

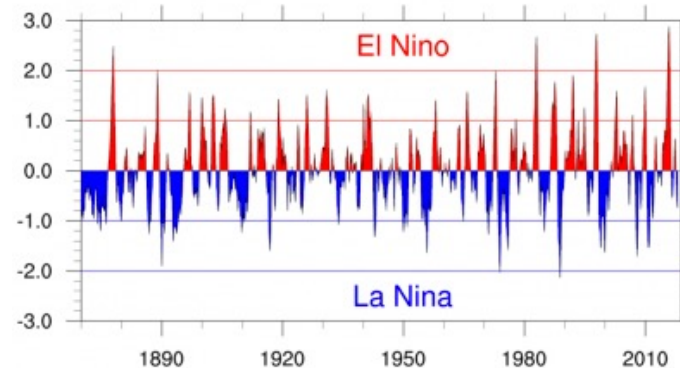


Atmosphere



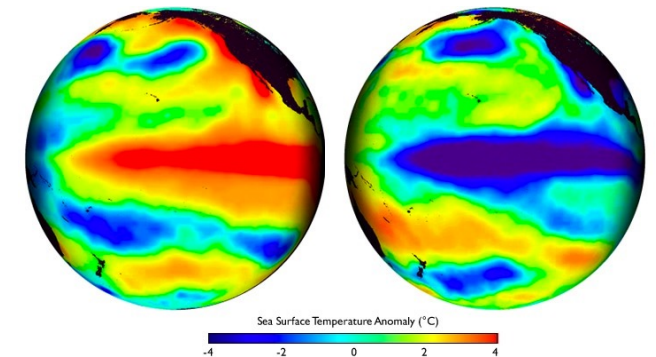
Ocean

El Niño-Southern Oscillation - ENSO



El Niño

La Niña



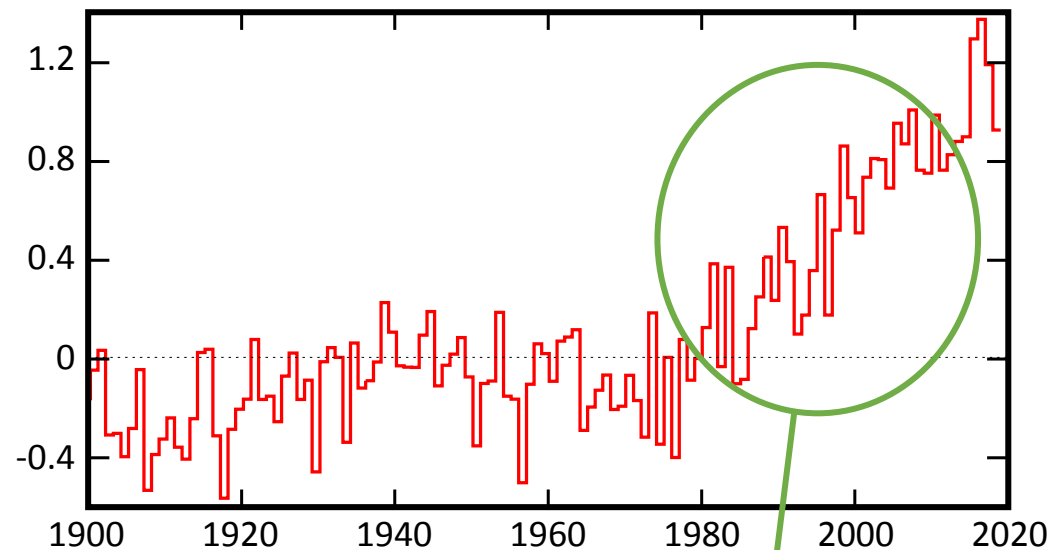
Sea Surface Temperature Anomaly

# Earth System Models for climate change attribution

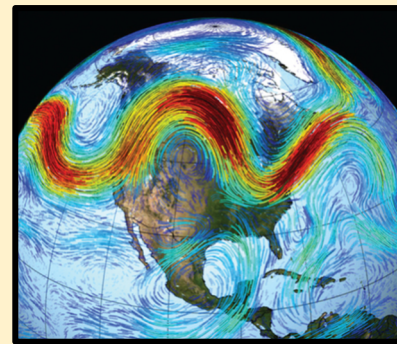
ESMs can help understand the main drivers of past changes in climate

## Internal Climate Variability

Global mean Surface Temperature anomaly (in K)



Some of the year-to-year changes in global mean temperature can be explained by ENSO variability

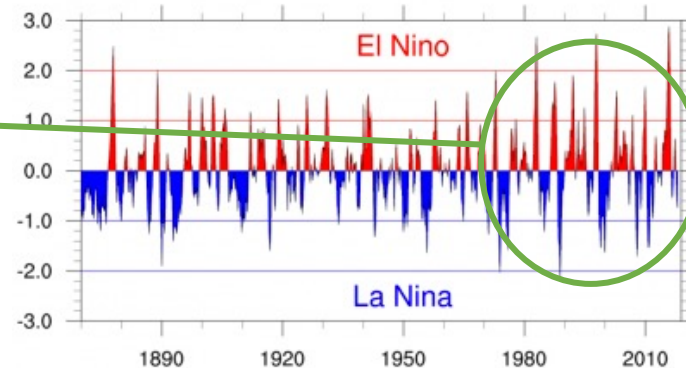


Atmosphere



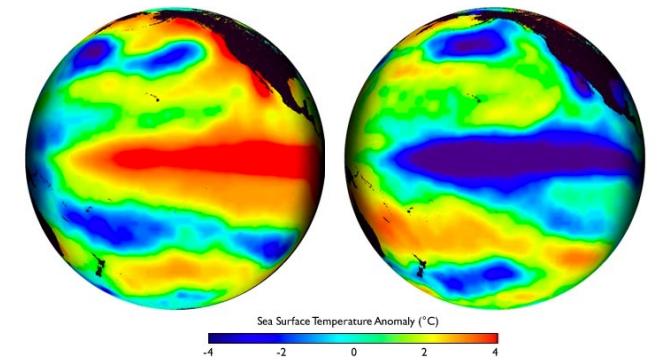
Ocean

El Niño-Southern Oscillation - ENSO



El Niño

La Niña



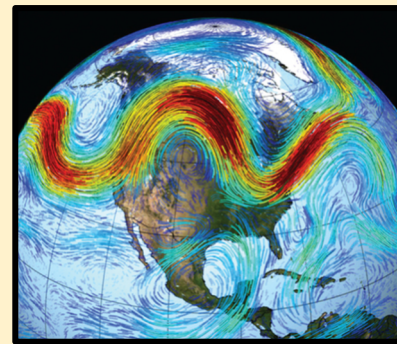
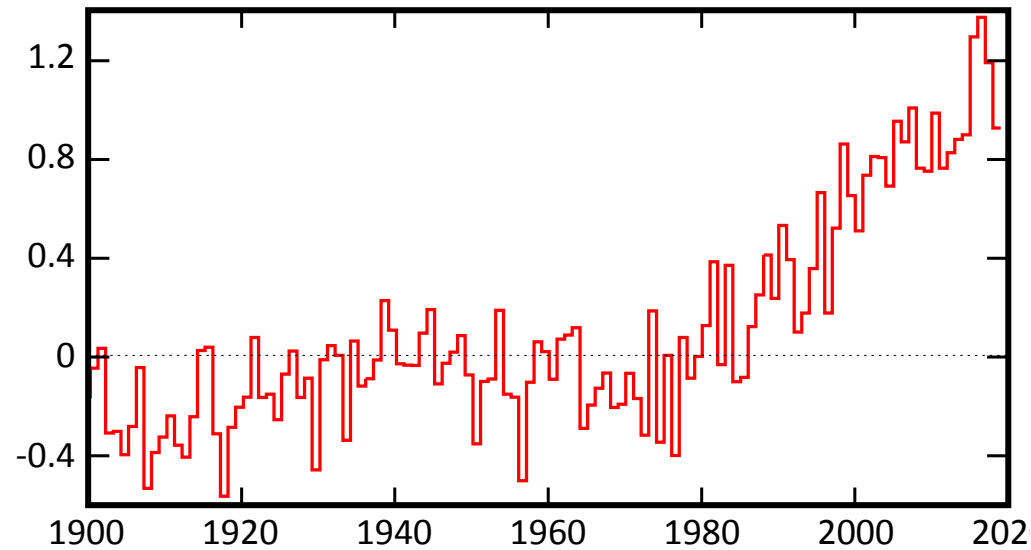
Sea Surface Temperature Anomaly

# Earth System Models for climate change attribution

ESMs can help understand the main drivers of past changes in climate

## Internal Climate Variability

Global mean Surface Temperature anomaly (in K)



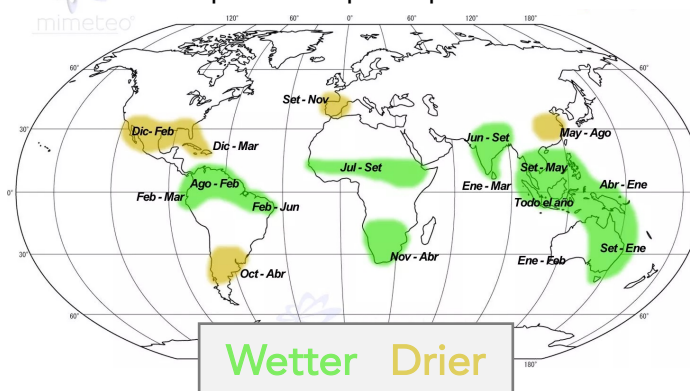
Atmosphere



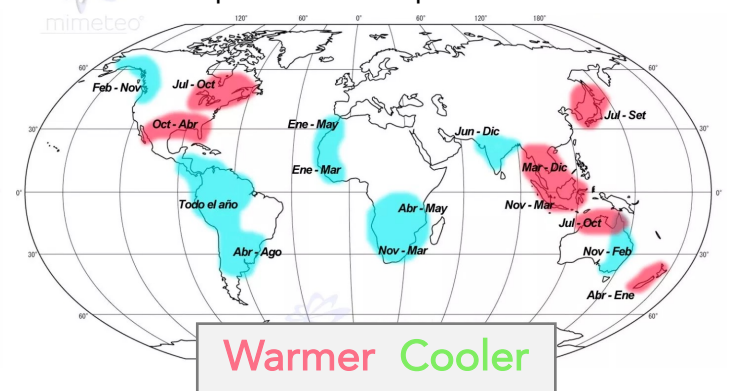
Ocean

ENSO also has numerous climate impacts at the regional scale

**La Niña**  
Impact on precipitation



**La Niña**  
Impact on temperature



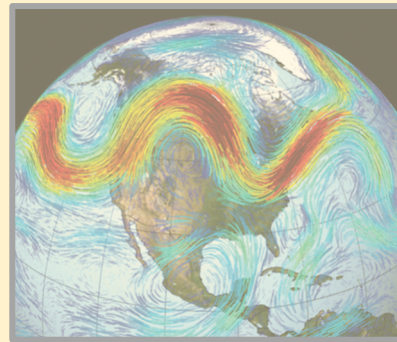
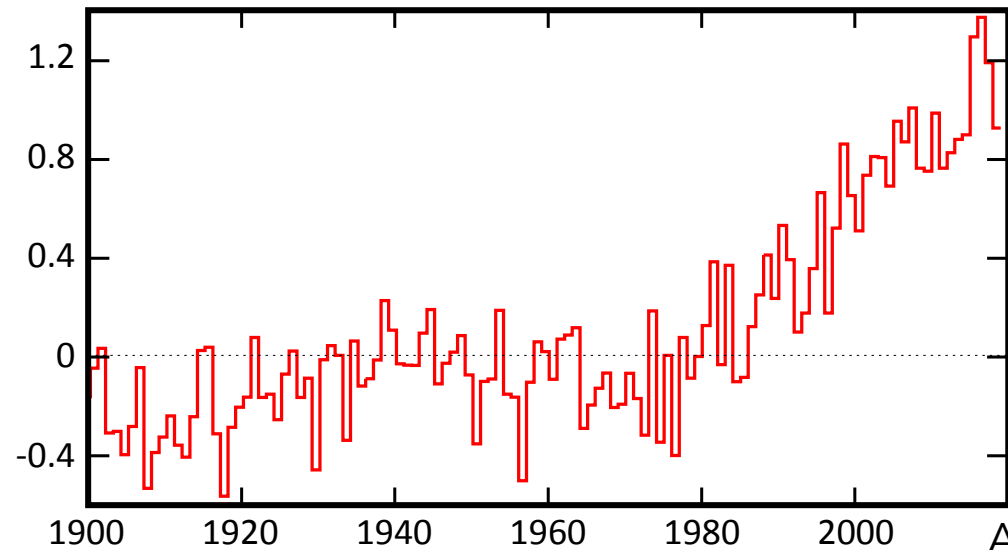


# Earth System Models for **climate change attribution**

ESMs can help understand the main drivers of past changes in climate

## Internal Climate Variability

Global mean Surface Temperature anomaly (in K)

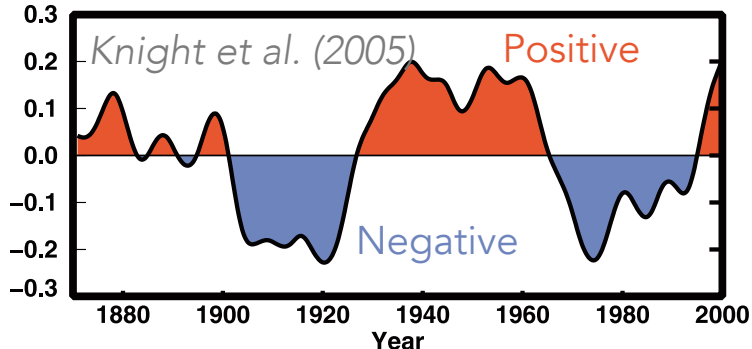


Atmosphere

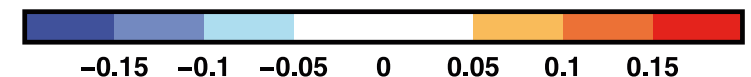
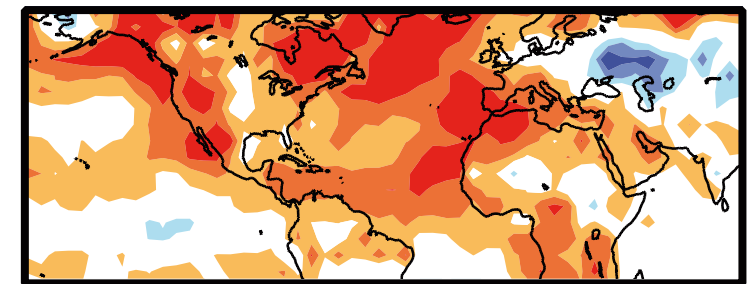


Ocean

Atlantic Multidecadal Variability - AMV



Positive phase AMV pattern

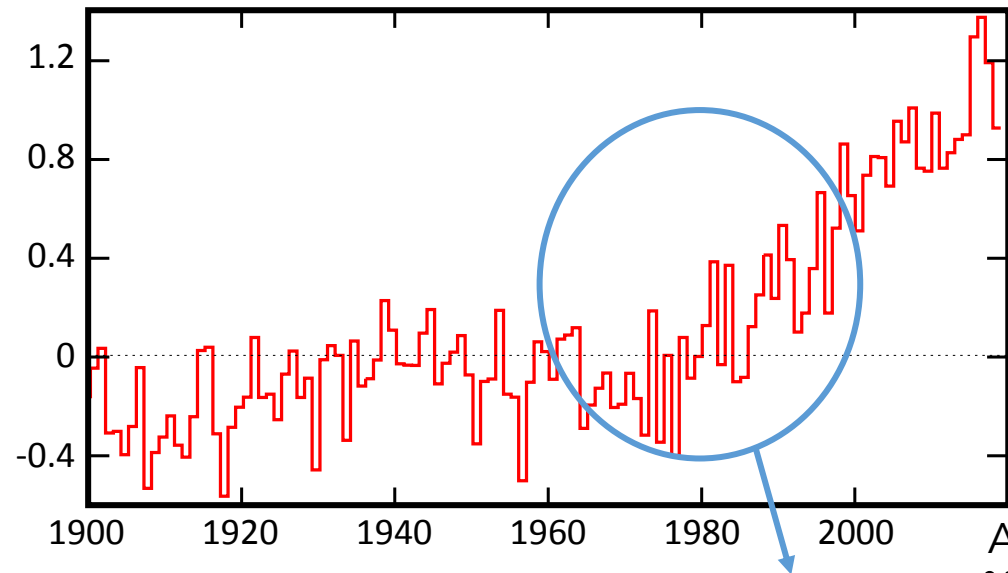


# Earth System Models for **climate change attribution**

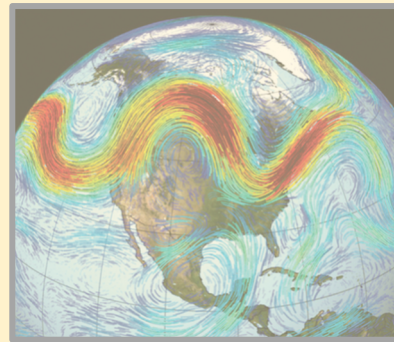
ESMs can help understand the main drivers of past changes in climate

## Internal Climate Variability

Global mean Surface Temperature anomaly (in K)



The AMV can explain some of the multidecadal modulations in the global mean temperatures

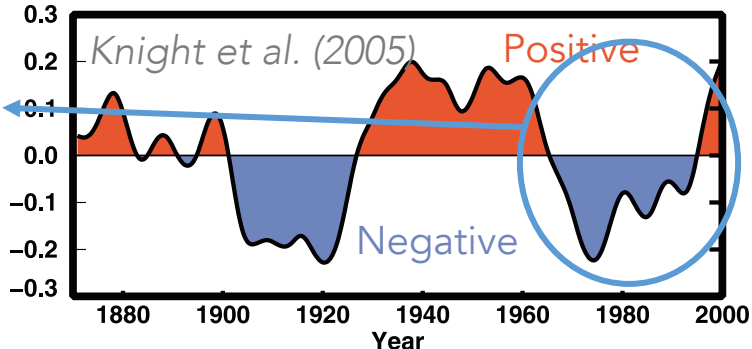


Atmosphere

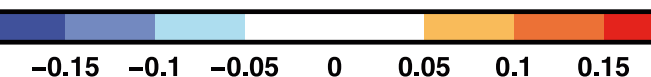
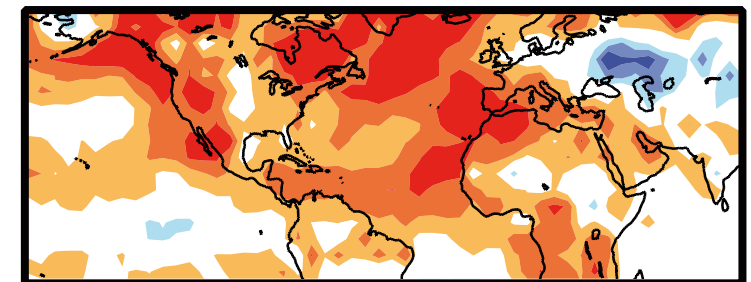


Ocean

Atlantic Multidecadal Variability - AMV



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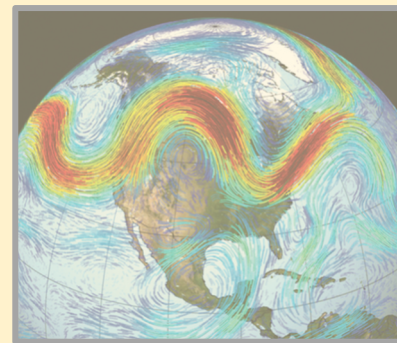
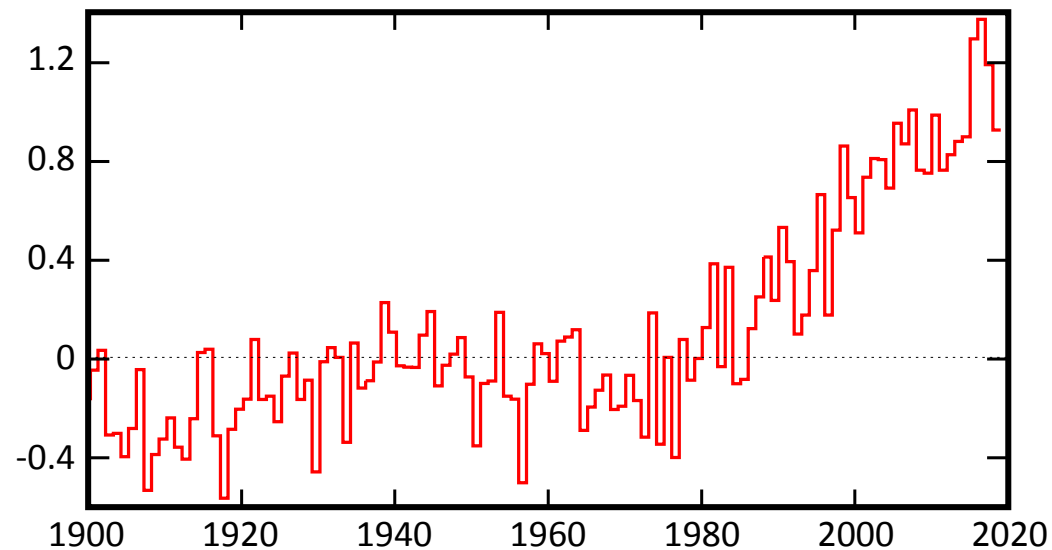


# Earth System Models for **climate change attribution**

ESMs can help understand the main drivers of past changes in climate

## Internal Climate Variability

Global mean Surface Temperature anomaly (in K)



Atmosphere

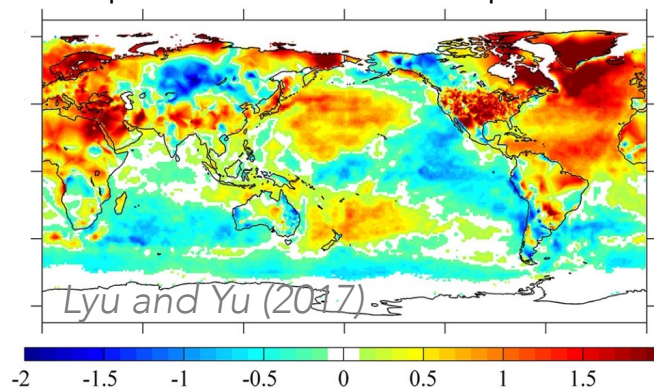


Ocean

AMV also has important climate impacts on its neighboring continents

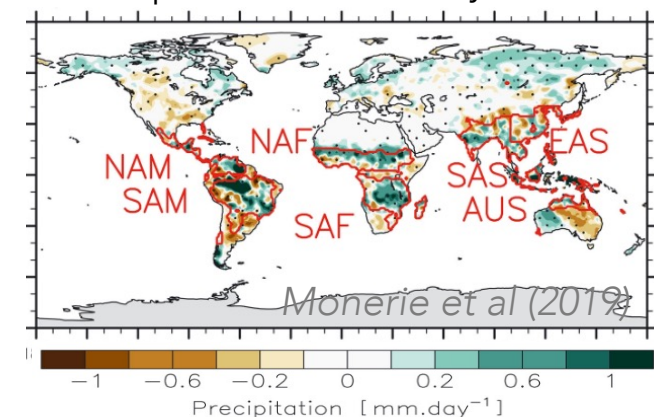
### Positive AMV

Impact on surface air temperature



### Positive AMV

Impact on monsoon systems

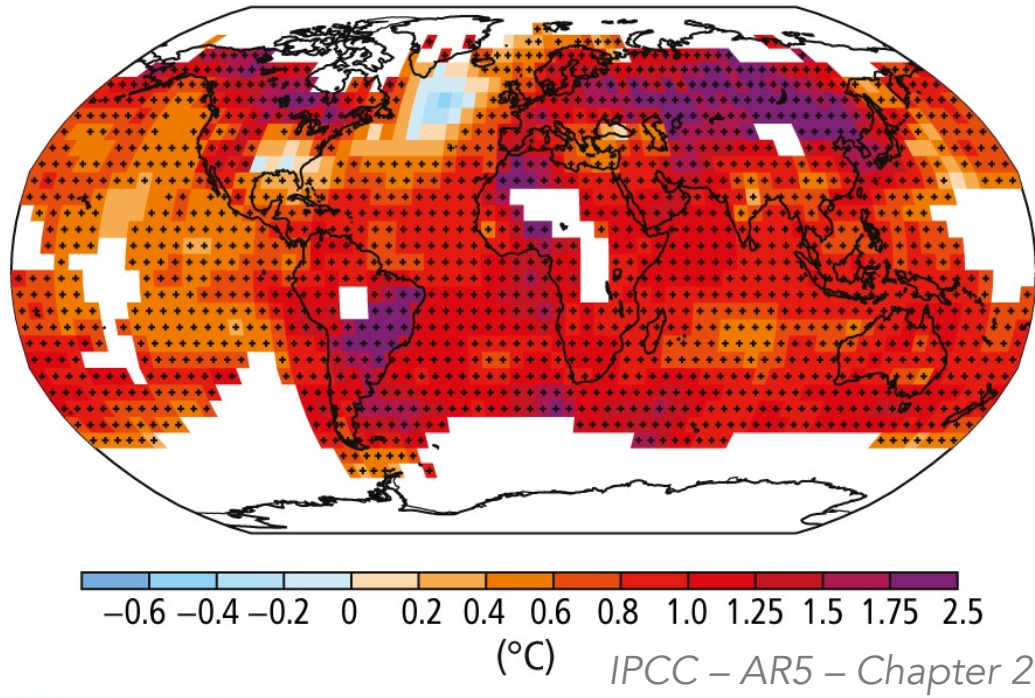




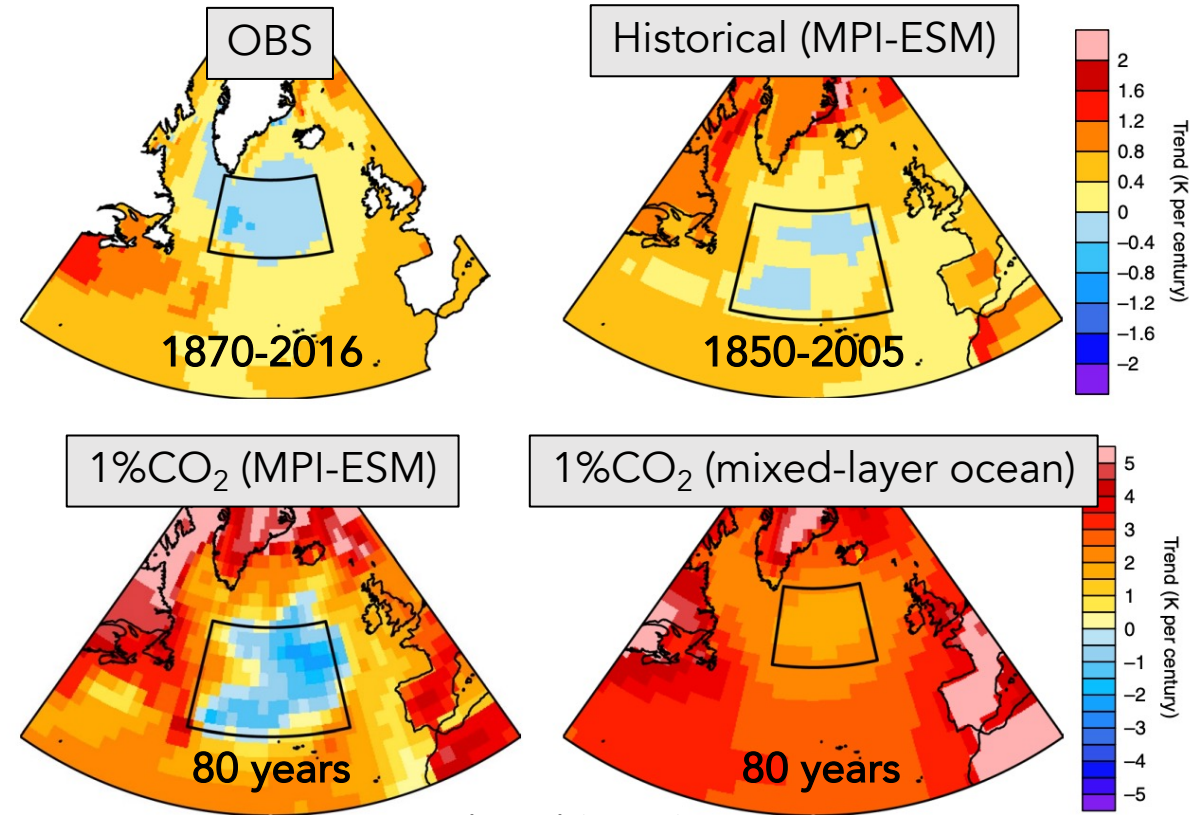
# Earth System Models for climate change attribution

ESMs can help understand the main drivers of past changes in climate

Observed Change in Surface Temperature (1901-2012)



Linear trends in Sea Surface Temperature (SST)

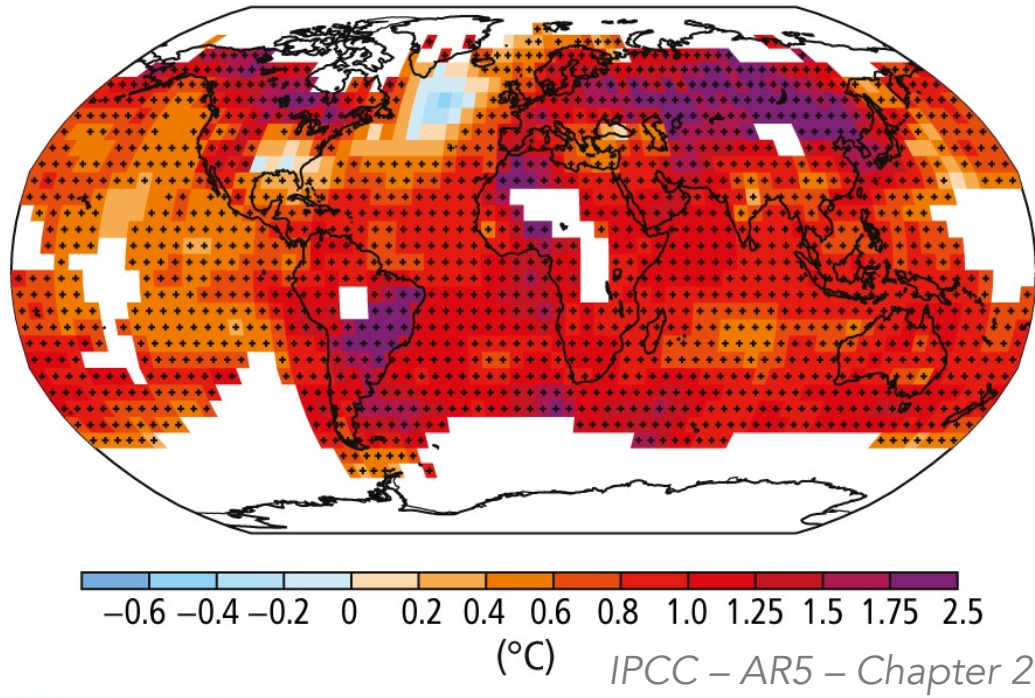




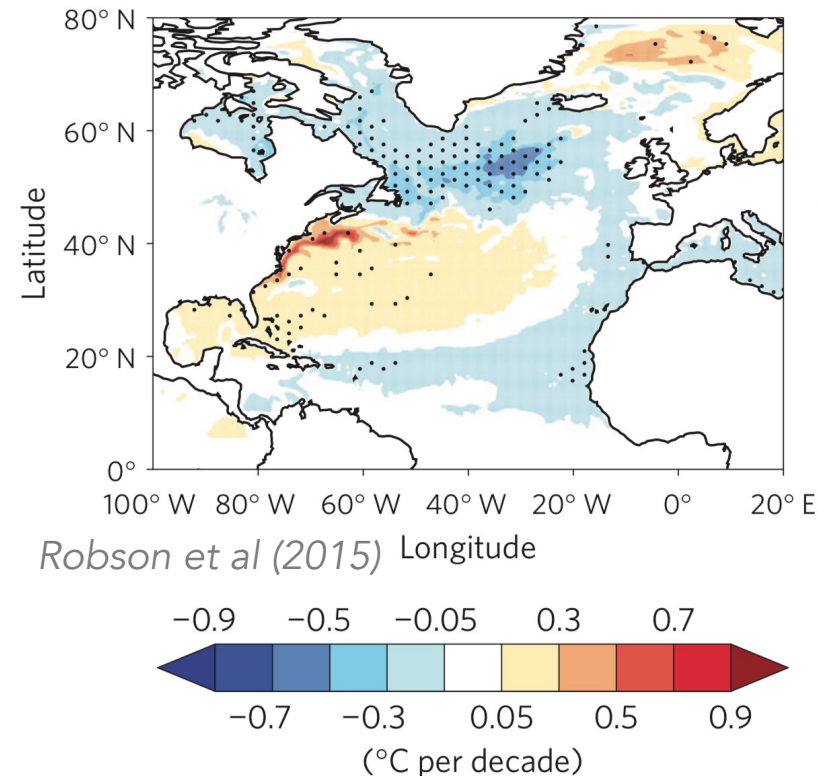
# Earth System Models for **climate change attribution**

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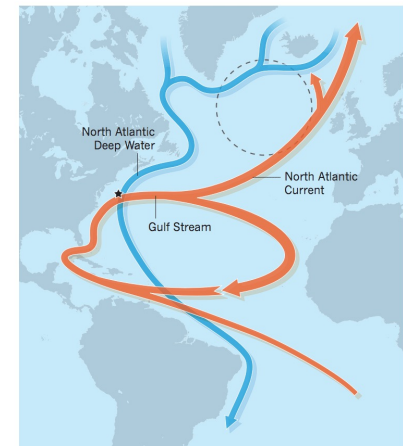
Observed Change in Surface Temperature (1901-2012)



Linear trends in SST following **unforced** reductions in Atlantic ocean circulation



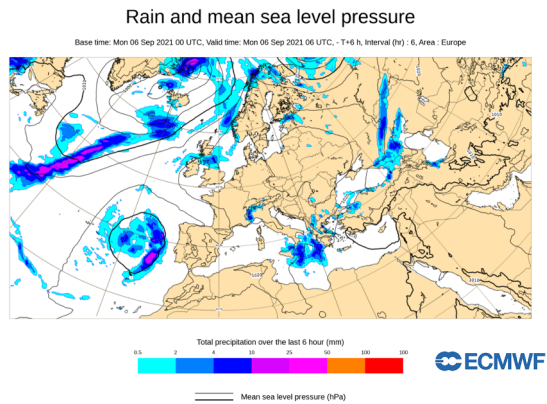
Schematic Atlantic ocean circulation



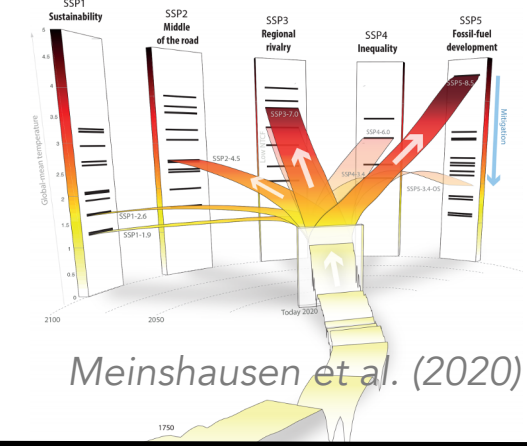
# Earth System Models for near-term climate prediction

## Fundamentals of climate prediction

### Weather forecasts



### Climate projections



Days

Weeks

Months

Seasons

Years

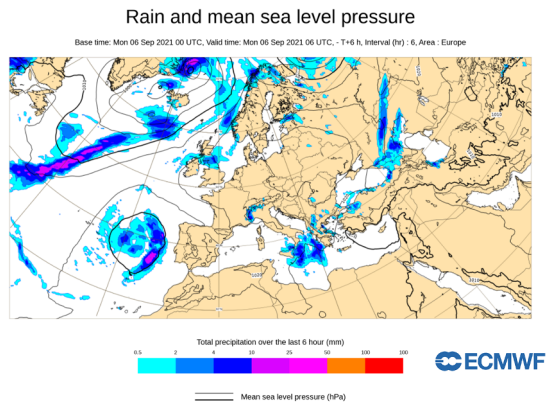
Decades

Centuries

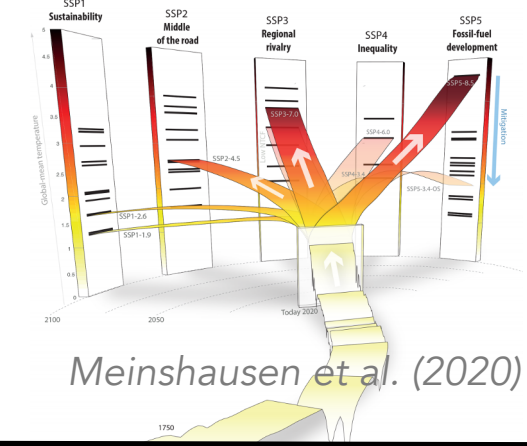
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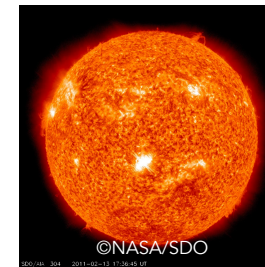
Months

Seasons

Years

Decades

Centuries



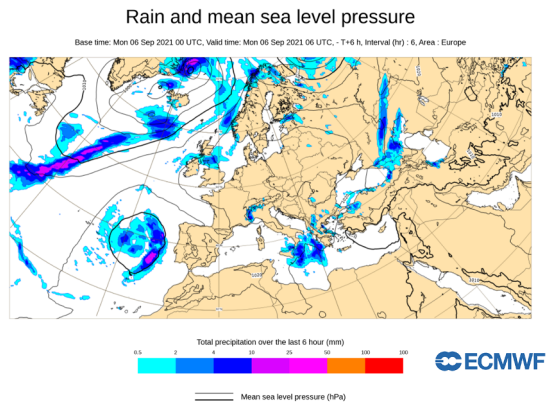
Good guess of **future changes in the forcing factors**  
[ BOUNDARY CONDITION PROBLEM ]



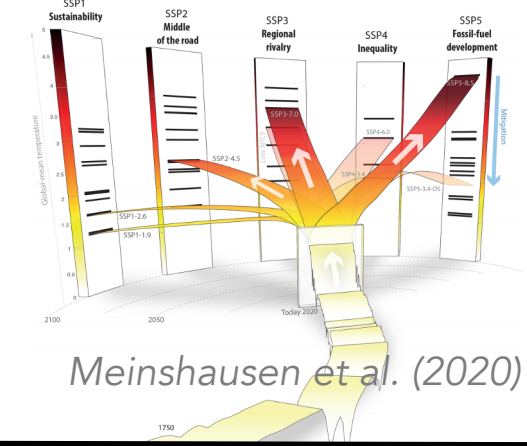
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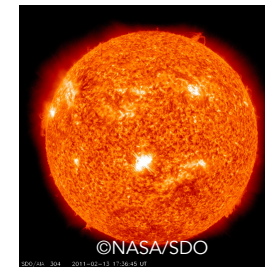
Seasons

Years

Decades

Centuries

Accurate constraint of the **current meteorological state**  
[ INITIAL VALUE PROBLEM ]



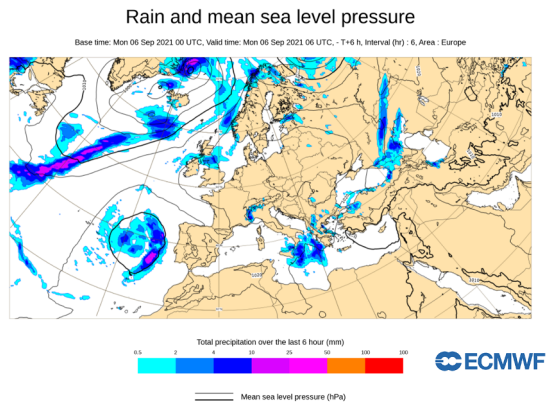
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# Earth System Models for near-term climate prediction

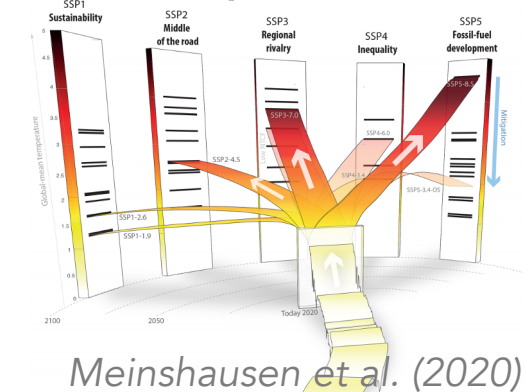
## Fundamentals of climate prediction

### Weather forecasts



In seasonal to decadal prediction  
both contributions matter !!

### Climate projections



Days

Weeks

Months

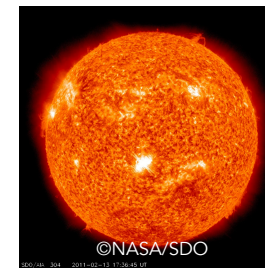
Seasons

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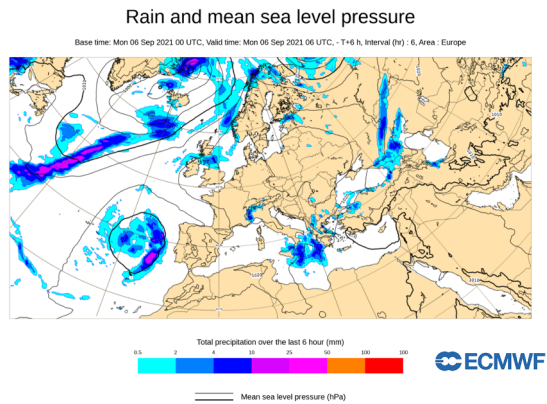


Good guess of **future changes in the forcing factors**  
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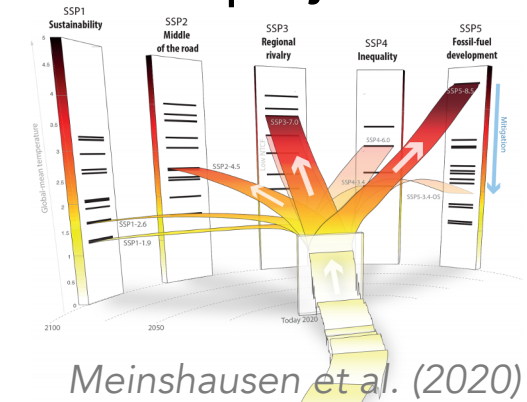
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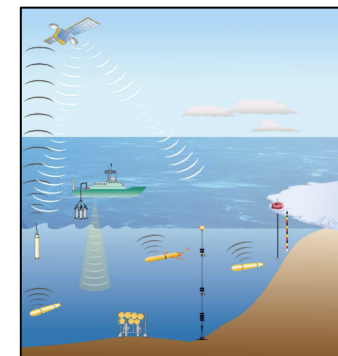
Years

Decades

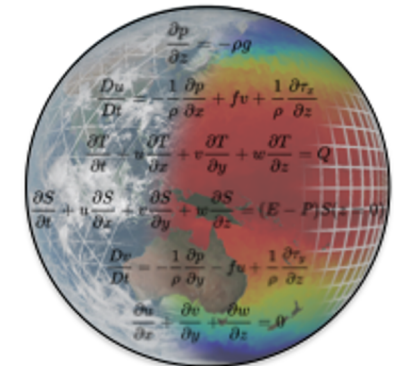
Centuries

Initialization of internal sources of predictability

Observations



Global Earth System Model



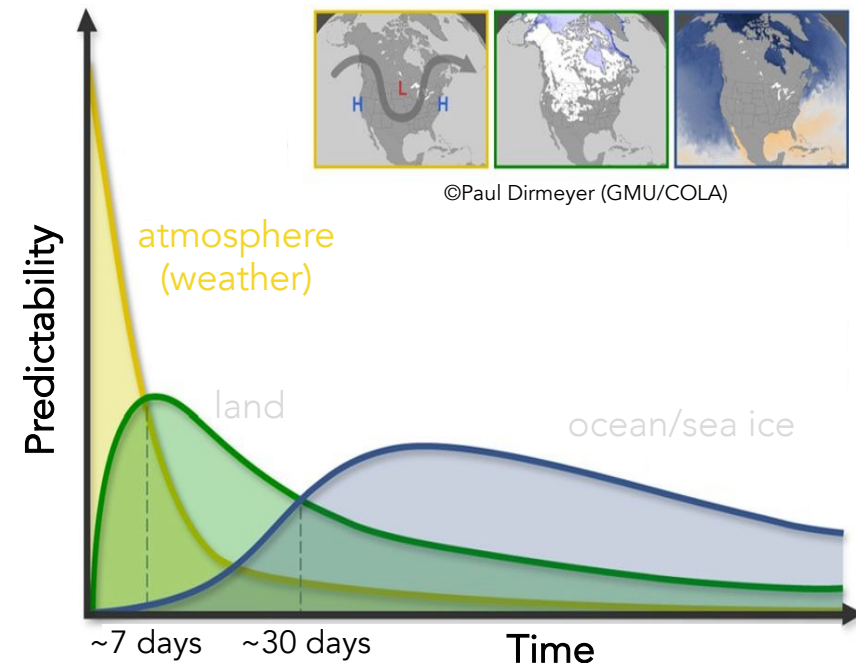
DATA ASSIMILATION

# Earth System Models for near-term climate prediction

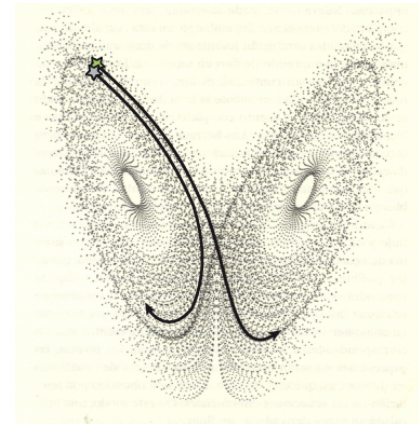
## Internal sources of predictability

Weather prediction

→ ~ 10 days

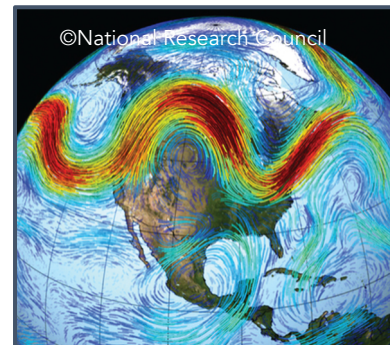


Mariotti et al (2018)



Due to the chaotic nature of atmospheric variability  
(butterfly effect)

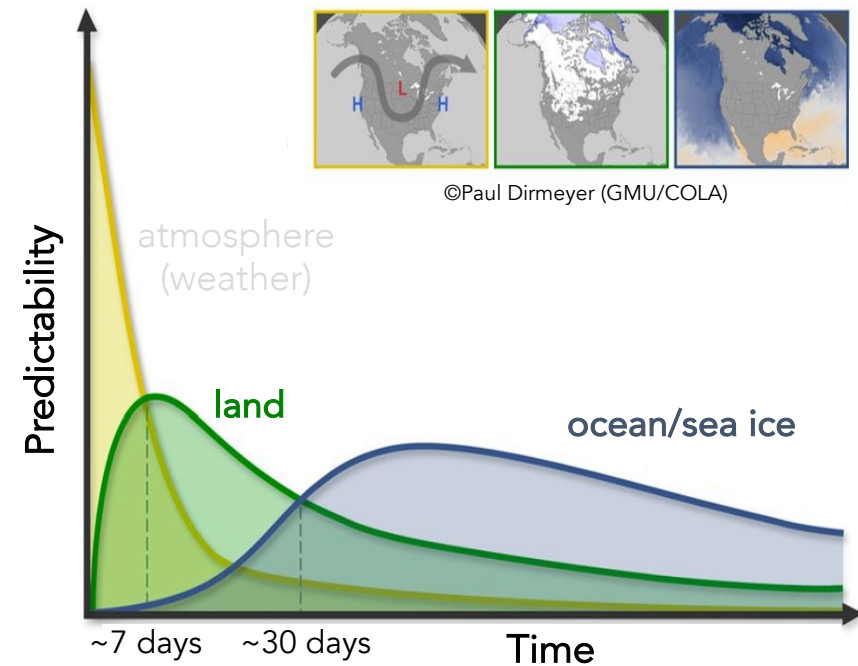
atmosphere





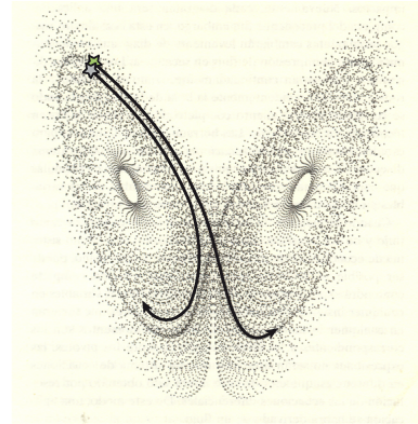
# Earth System Models for near-term climate prediction

## Internal sources of predictability



Mariotti et al (2018)

Weather prediction → ~ 10 days



Due to the chaotic nature of atmospheric variability (butterfly effect)

Climate prediction → weeks to decades

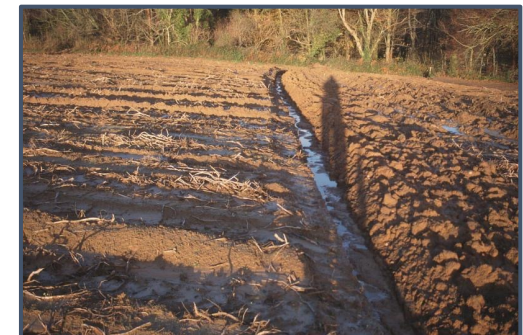
ocean



sea ice



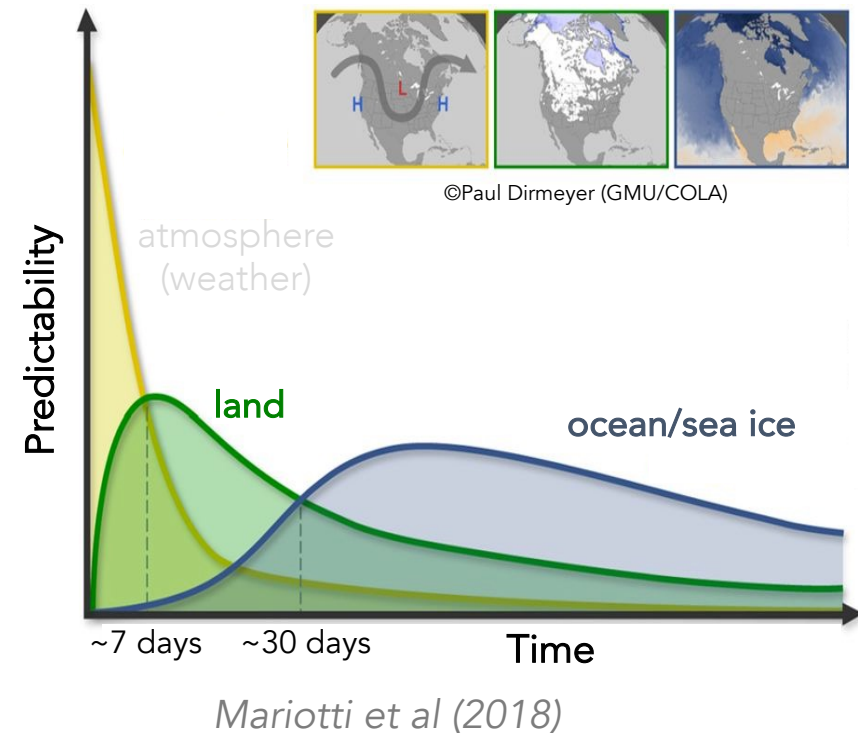
soil moisture



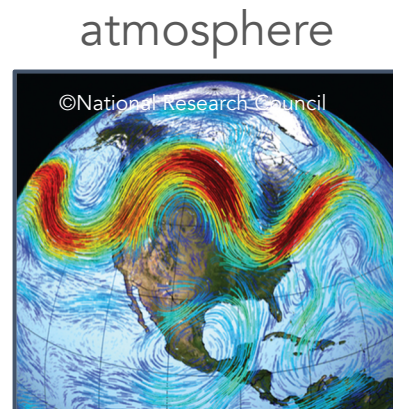
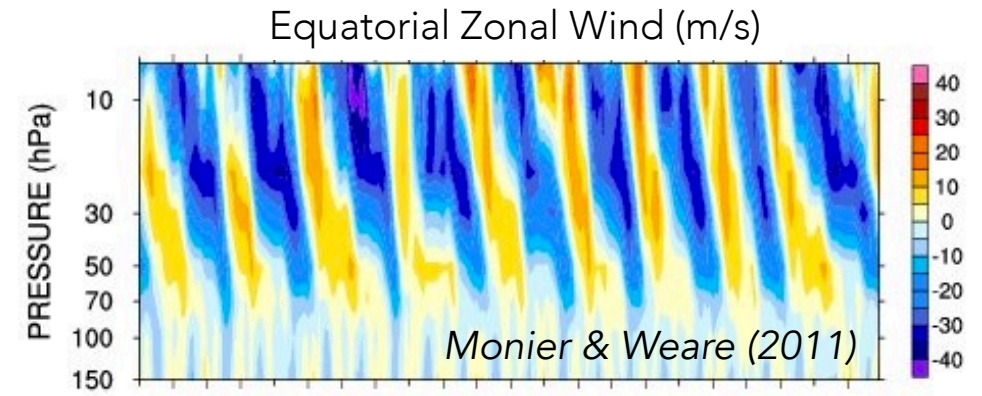


# Earth System Models for near-term climate prediction

## Internal sources of predictability



The atmosphere can also provide memory beyond a month:  
The **Quasi-Biennial Oscillation (QBO)**

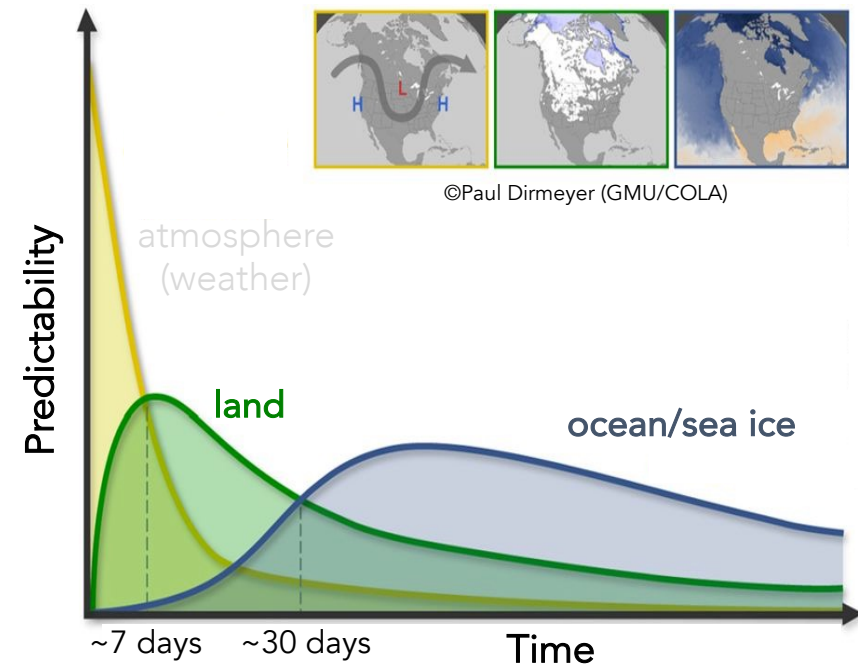


Through a modulating effect on wave propagation, the **QBO** can impact the **polar vortex strength** and contribute to Northern Hemisphere **predictability** at **seasonal and interannual scales**.

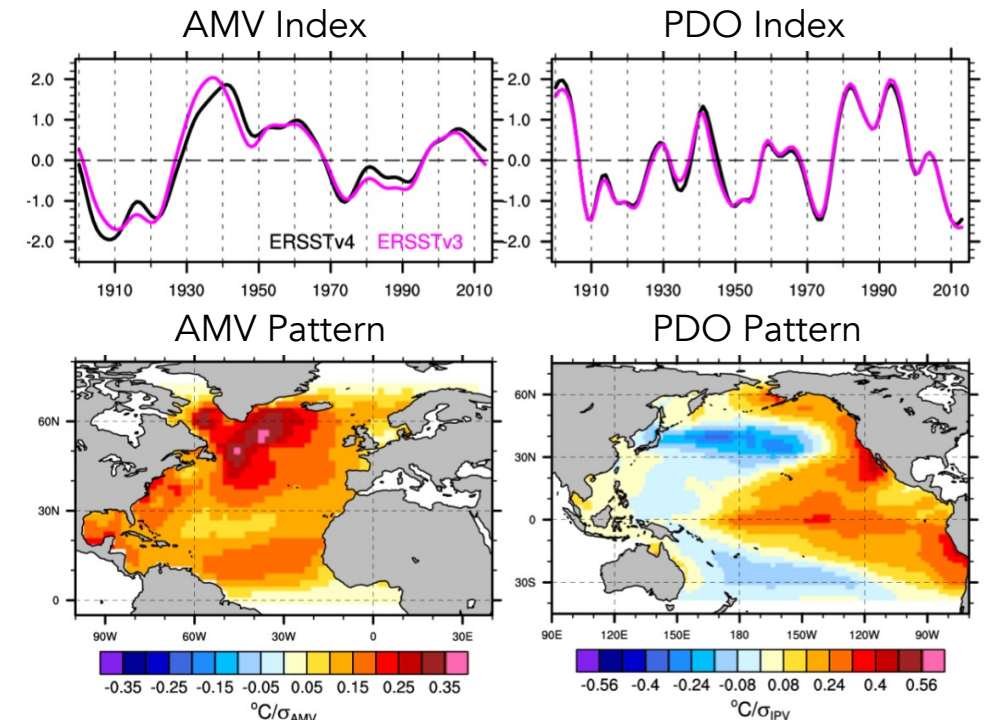
# Earth System Models for near-term climate prediction

## Internal sources of predictability

The ocean exhibits **modes of decadal variability** both in the **Atlantic and Pacific** basins



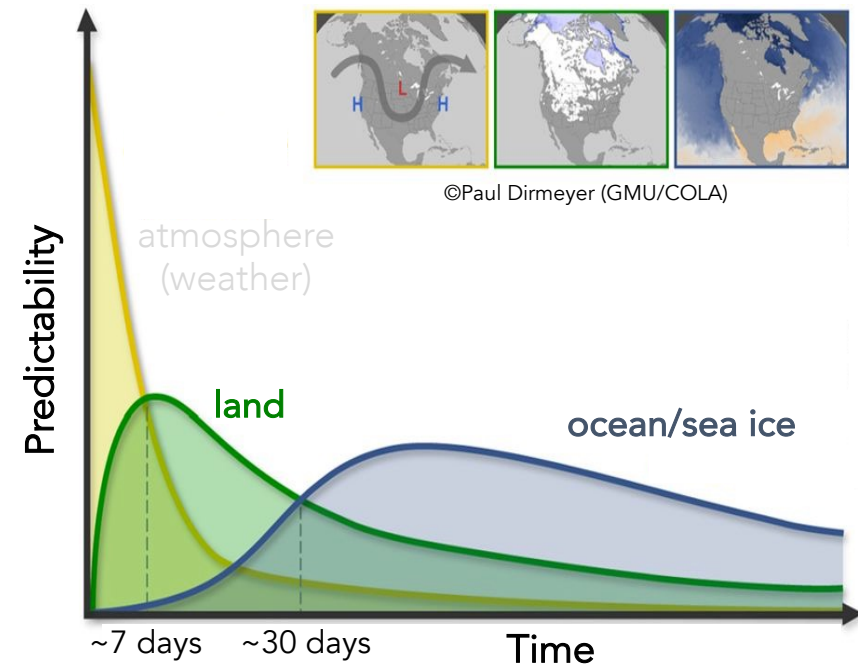
Mariotti et al (2018)



Cassou et al,  
Technical Note for DCP-Component C

# Earth System Models for near-term climate prediction

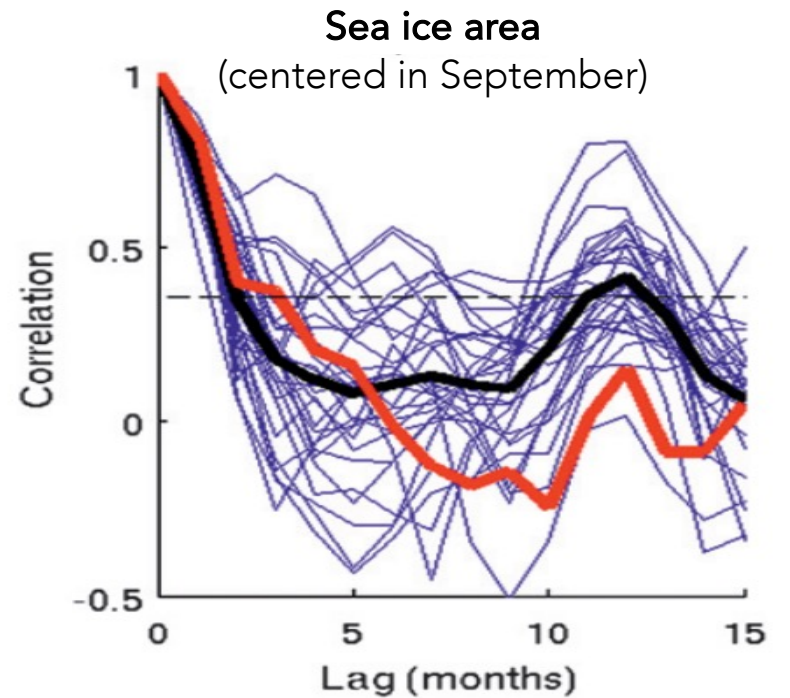
## Internal sources of predictability



Mariotti et al (2018)



Re-emergence mechanisms in Arctic sea ice provide memory and thus **predictability at annual scales**

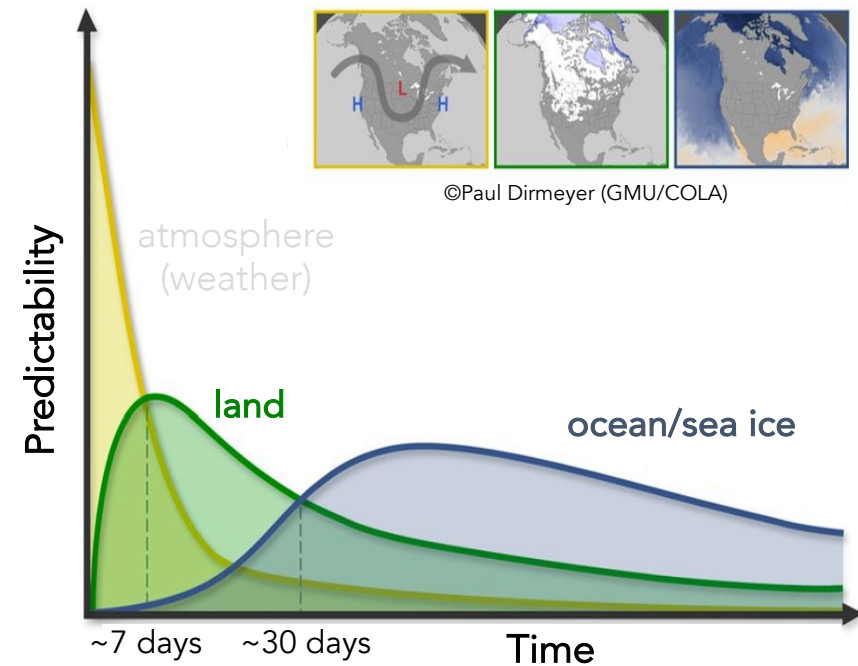


Blanchard-Wrigglesworth et al (2011)



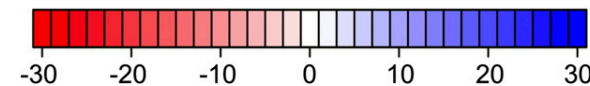
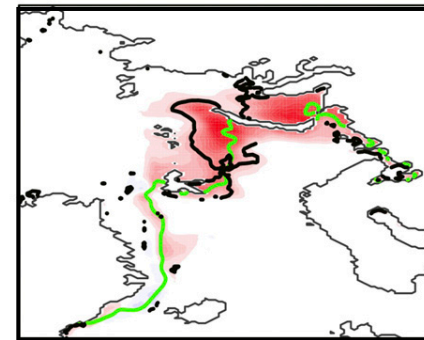
# Earth System Models for near-term climate prediction

## Internal sources of predictability

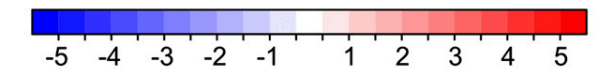
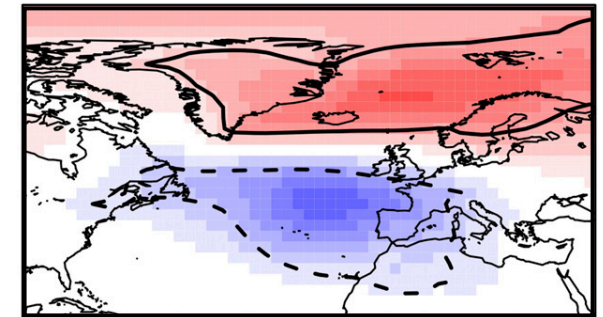


Mariotti et al (2018)

1st EOF of November  
Sea Ice Cover (SIC)



Predicted DJF  
Sea Level Pressure



García-Serrano et al (2014)

sea ice



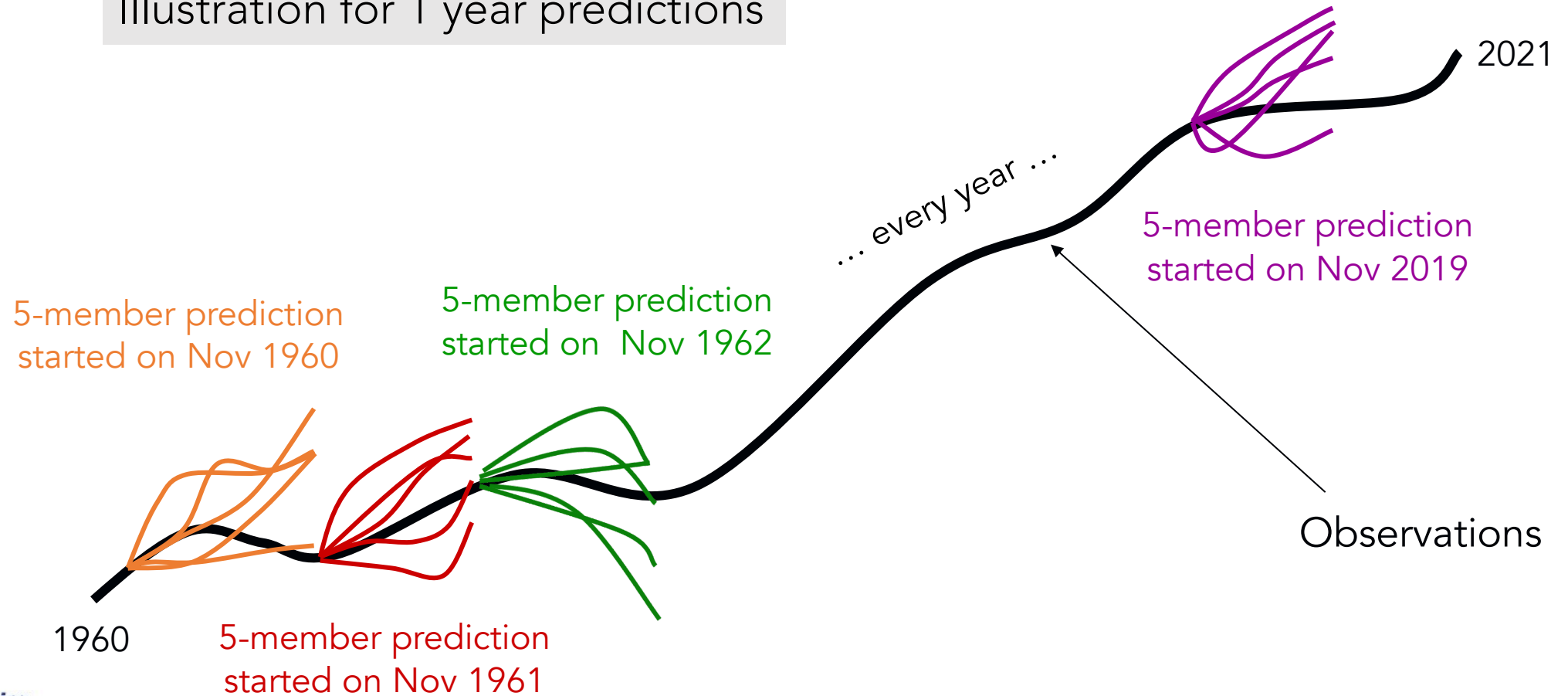
This reemergence could translate into **predictability beyond the Arctic**, as several studies report important impacts of Arctic sea loss on the climate of the mid-latitudes



# Earth System Models for near-term climate prediction

Evaluating the skill of climate prediction systems

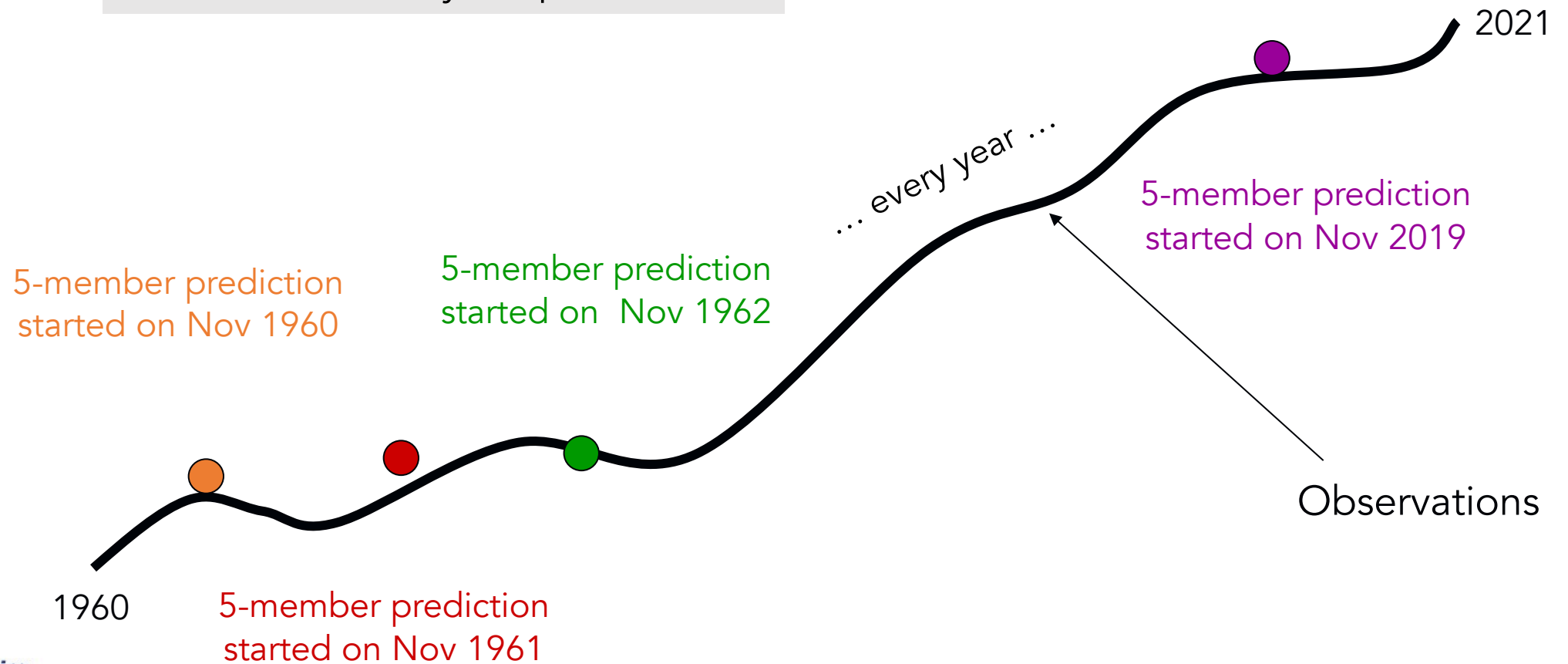
Illustration for 1 year predictions



# Earth System Models for near-term climate prediction

Evaluating the skill of climate prediction systems

Illustration for 1 year predictions

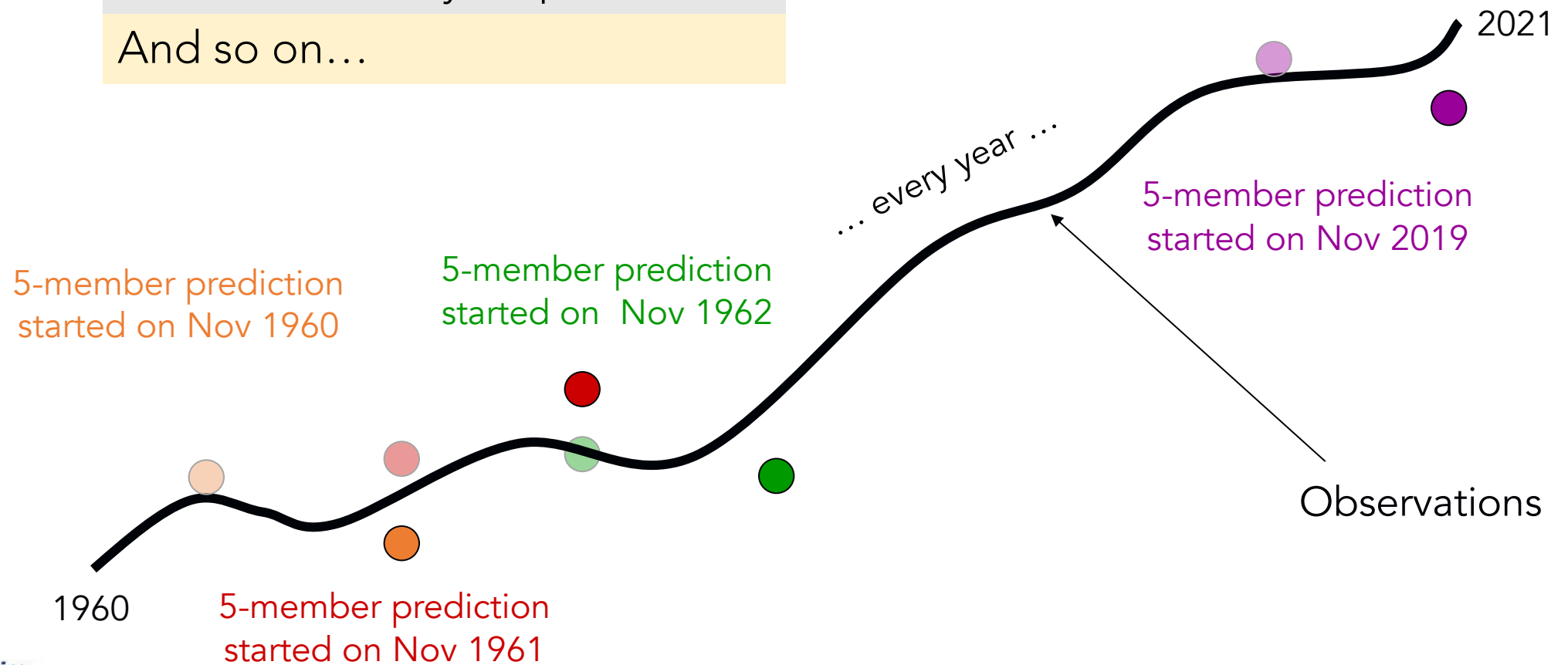


# Earth System Models for near-term climate prediction

Evaluating the skill of climate prediction systems

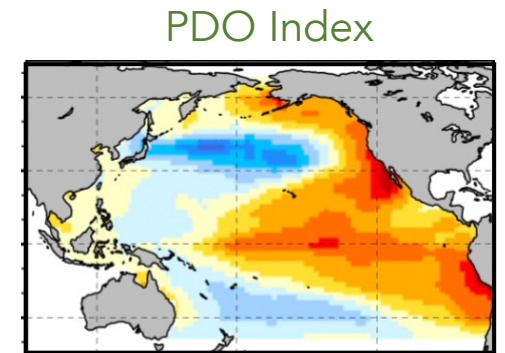
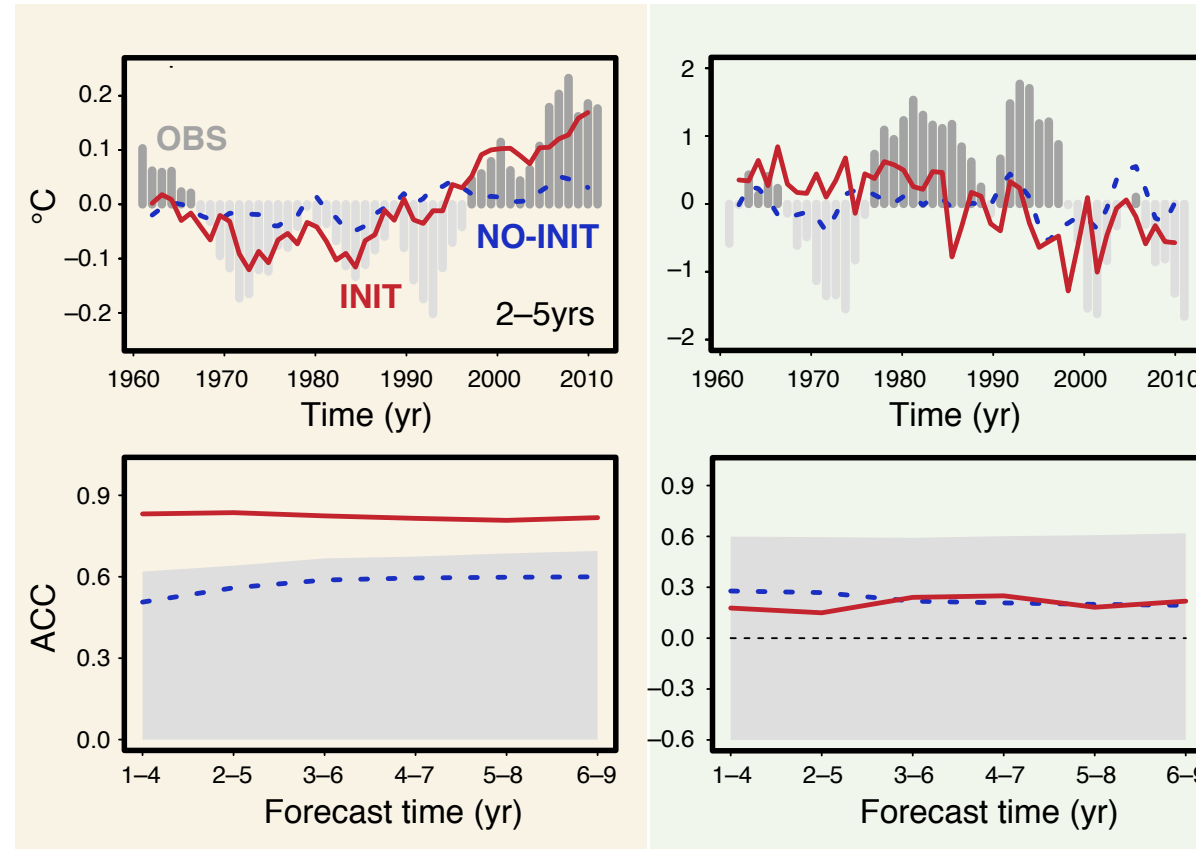
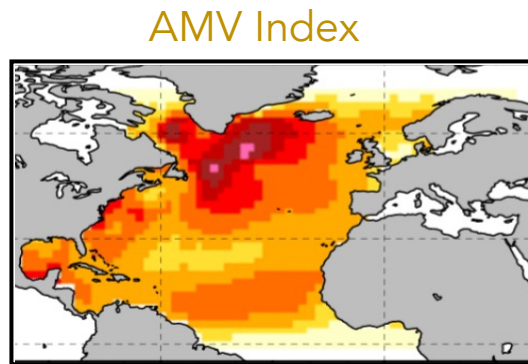
Illustration for 2 year predictions

And so on...



# Earth System Models for near-term climate prediction

An example of skill in decadal climate predictions



*Doblas Reyes et al (2013)*

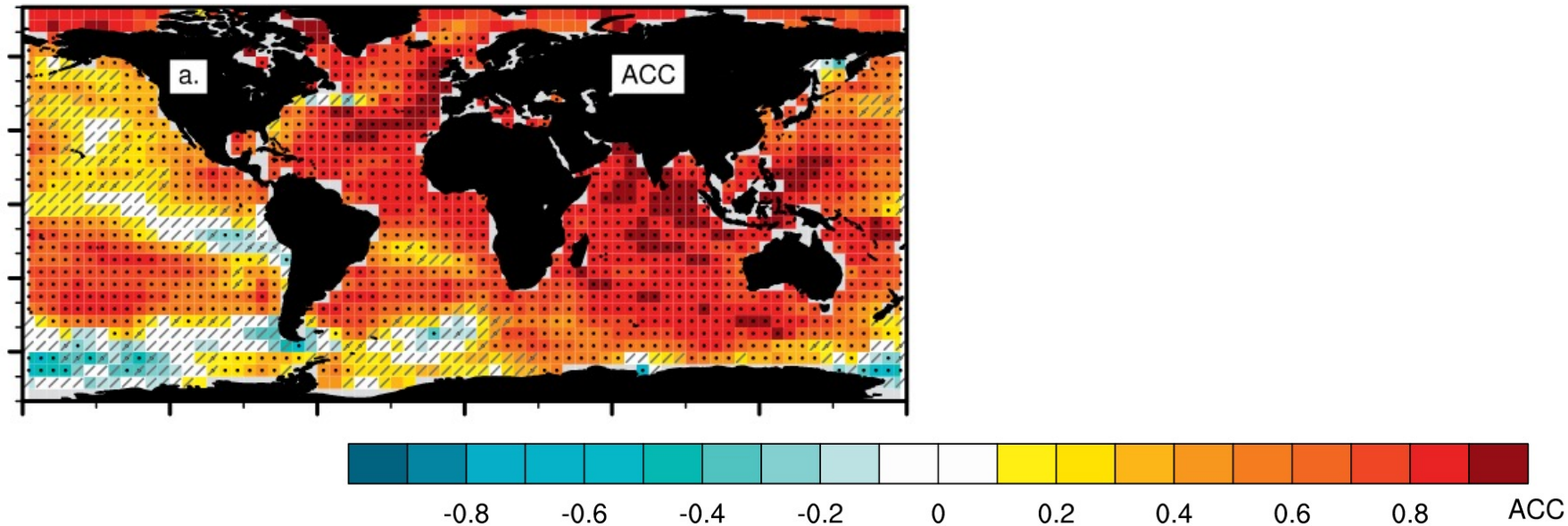
Only for the AMV the initialised forecasts show significant predictive skill and beat persistence for predictive horizons of up to 9 years



# Earth System Models for near-term climate prediction

Attributing skill in decadal climate predictions: internal vs forced

Correlation Initialised Predictions vs OBS  
*Forecast years 1 to 5*



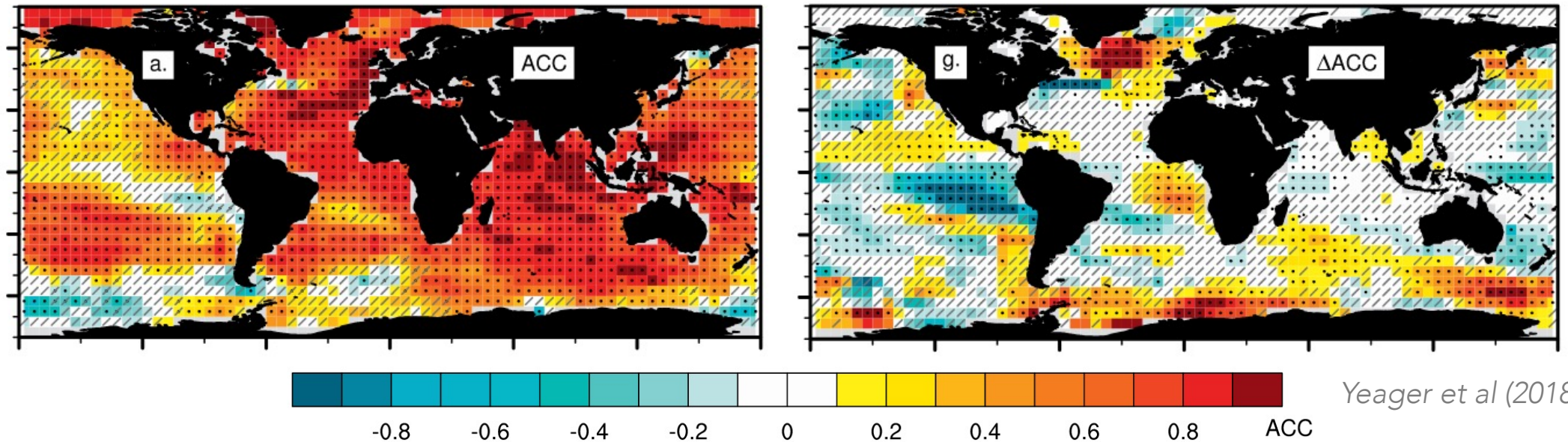
*Yeager et al (2018)*

# Earth System Models for near-term climate prediction

Attributing skill in decadal climate predictions: internal vs forced

Correlation Initialised Predictions vs OBS  
*Forecast years 1 to 5*

Correlation difference Initialized vs Uninitialised  
*Forecast years 1 to 5*



Most of the skill in multi-year predictions come from the external forcings, with only a few regions like the North Atlantic showing important skill from initialization of internal variability

# Take home messages

- Earth system models are our main tool to understand the climate system and its changes, and have grown in complexity and accuracy with the major improvements in high-performance computing
- Climate variability and change are governed by the evolution of both natural and anthropogenic forcing factors, and can respond also to internal climate processes
- While the influence of radiative forcings tend to dominate the global scale changes, internal variability processes can produce important regional changes in regions like the North Atlantic or the Tropical Pacific, and impact continental areas via atmospheric teleconnections
- Models can be used to successfully predict the climate from months to several years (and even decades) ahead



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